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# Alcator C-Mod Program, Plans and Budgets

OFES Budget Planning Meeting  
March 14, 2001

E. S. Marmor  
R.R. Parker

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# Outline



- 
- Research Paths and FESAC/IPPA
  - Collaborations
  - Advanced Tokamak Research
  - Compact High Field Studies
  - Upgrades and Operations Plans; Schedule
  - Milestones and Plain English Goals
  - Personnel and Budgets
  - Consequences of 10% Cut
  - Benefits of 10% Increment
  - Lower Hybrid Project

# C-Mod Research Organized along 2 Parallel, Complementary Paths



1. **Advanced Tokamak (IPPA Objectives 3.1 and 3.2)**
  - ❖ Quasi-steady-state ( $t > \tau_{L/R}$ ), high bootstrap fraction, RF current and flow profile control
  - ❖ New tool: Lower Hybrid current drive – 3 MW at 4.6 GHz; first experiments in spring of 2003
2. **Compact, High Field, High Pressure (IPPA 3.2 and 3.3)**
  - ❖ Broaden the physics basis for the compact, high field approach to ignition
  - ❖ Inner wall/divertor upgrade – Operation to 2 MA at 8 Tesla; spring of 2002

# Unique Aspects and Strengths of C-Mod

## ⇒ Address Key Questions



- **Unique long pulse capability** (relative to skin and L/R times) in highly shaped, diverted plasma; B > 4 T IPPA 3.1 (Profile Control); 3.2 (High  $\beta$  Stability and Disruption Mitigation)
  - Quasi-steady lower hybrid driven AT scenarios
- **High performance, compact, high field capability** 3.3 (Burning Plasma); 3.2 (High  $\beta$  Stability and Disruption Mitigation)
  - Address issues for compact, high-field ignition approaches
- **Exclusively RF driven** 1.3 (Wave Particle Interactions); 4.1 (Plasma Technologies)
  - Heating decoupled from particle sources
  - No external momentum sources
  - Reactor-relevant regimes for transport (1.1), MHD (1.2), AT studies (3.1, 3.2)
- **Unique dimensional parameters**, but comparable to larger tokamaks in dimensionless parameters 1.1 (Turbulence and Transport); 1.4 (Multiphase Interfaces); 3.3 (Burning Plasma); 1.2 (Macroscopic Stability)
  - Key points on scaling curves
  - Test sensitivities to non-similar processes (radiation, neutrals, etc.)
- **Very high scrape-off layer power density** 1.4 (Multiphase Interfaces)
  - Unique divertor regimes, reactor prototypical
- **High Z metal walls** (also reactor prototypical) 4.1 (Plasma Technologies); 1.4 (Multiphase interfaces)
  - Unique recycling properties; generic MFE challenge

# Scientific Topical Groups Support and Inform our Progress along the 2 Paths

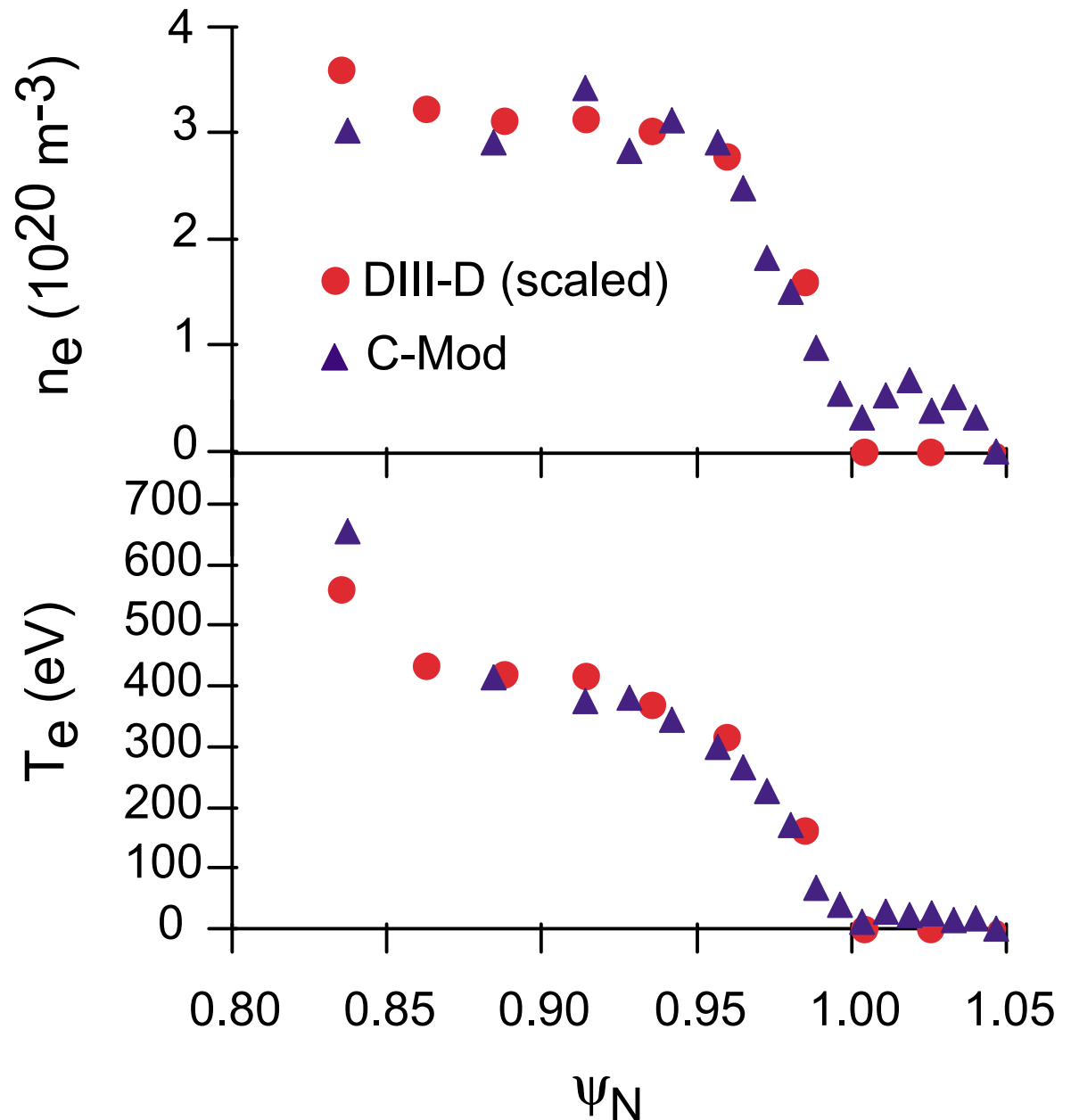


- 
- Core Transport ([IPPA 1.1 Turbulence and Transport](#))
    - Critical gradients & marginal stability; ITBs; Fluctuations & turbulence; Rotation; Integrated modeling
  - MHD ([1.2 Macroscopic Stability](#))
    - Stability (Mercier, Double tearing, NTM's, Ballooning); Disruptions (Neutral point, Halo & eddy currents); Active MHD spectroscopy
  - ICRF ([1.3 Wave Particle Interactions](#))
    - Heating (FW, MC); Flow drive; Current drive; ITB dynamics; Rotation
  - Divertor/Edge ([1.4 Multiphase Interfaces](#))
    - SOL  $\perp$  transport; fluctuations;  $\parallel$  energy, particle & momentum transport; Impurity generation & transport; Detachment physics; Density control; Power & particle exhaust; Edge core compatibility
  - Pedestal Physics ([1.1](#), [1.2](#), [1.3](#), [1.4](#))
    - Edge fluctuations (EDA, ELMs, Pedestal Transport); L/H threshold & dynamics; Neutrals; Density limits; Dimensionless similarity

# Pedestal Similarity Studies with DIII-D Show Remarkable Agreement



- Matched  $\beta$ ,  $v^*$ ,  $\rho^*$  at top of pedestal
- Matched plasma shapes, topology
- DIII-D data scaled dimensionlessly
- Highlights importance of extremely high resolution diagnostics for pedestal measurements



# Collaborations are Integral Part of the Project



- 
- PPPL
    - ICRF physics and modeling, antenna upgrades, operations
    - Diagnostics (MSE, ECE, reflectometry, fluctuation imaging)
    - Lower Hybrid current drive project
    - Advanced Tokamak physics
    - Comparisons with physics-based transport models
    - Divertor modeling
  - University of Texas F.R.C.
    - DNB operation and maintenance
    - DNB diagnostics (CXRS, BES)
    - ECE diagnostics
    - Reciprocating turbulence probe
    - Fluctuation physics
  - Scientists from approximately 40 other institutions involved in smaller scale collaborations
    - Contribute to all aspects of the program, especially **theory and modeling**

# MFE Goal 1: Advance fundamental understanding and enhance predictive capability through **comparison of well-diagnosed experiments, theory and simulation.**



## Theory/Modeling accomplished through collaborations

- Domestic collaborations include:
  - MIT Theory: Catto, Hastie, Porcelli, Ramos, Bers, Ram, Bonoli, Sigmar, Coppi, Sugiyama
  - PPPL: Perkins, White, Mikkelsen, Stotler, Zweben, Phillips
  - ORNL: Carreras, Hicks, Batchelor
  - Maryland: Dorland, Drake, Jenko, Rogers
  - LLNL: R. Cohen, Nevins, Xu, Fournier, Wan, Scott
  - Lodestar: Myer
  - UCSD: Krasheninnikov
  - NYU: Chang
  - Notre Dame: Safranov
  - Alaska: Newman
  - Texas: Ross, Berk, Kotschenreuther
  - Lehigh: Bateman, Kritz
  - Southeastern Louisiana U.: McCarthy
- International collaborations include:
  - Toronto: Elder, Lisgo, Stangeby
  - Culham: Helander, Wilson
  - JAERI: Nakamura, Ide
  - KFA Julich: Rogister, Reiter
  - IPP Garching: Brambilla
  - Ecole Royale Militaire: Evrard, Ongena
  - CEA Cadarche: Eriksson
  - Chalmers U.: Bondeson, Fulop
  - IPP Griefswald: Bonnin
  - NIFS/LHD: T. Kato

*"We congratulate the C-Mod team for their success in attracting theory and modeling collaborators. The scientific atmosphere, the openness and accessibility of data, and the flexibility in incorporating ideas into the experimental program are major attractions for collaborators." C-Mod PAC, March 1, 2001.*



# Advanced Tokamak Research



- Target scenario
  - High Bootstrap Fraction ( $\sim .7$ )
  - High  $\beta_N$  ( $\sim 3$ )
  - Non-inductive current sustainment  $t \sim \tau_{L/R} \gg \tau_{\text{skin}}$
  - All RF driven (6MW ICRF + 3 MW LHCD)
    - No particle or momentum sources
- Requirements
  - Confinement (control of edge + internal transport)
  - Impurity Control
    - L-mode or EDA H-Mode edge
  - Efficient ICRF heating
  - Density and density profile control
  - Efficient off-axis current drive
    - LHCD more efficient than ECCD
  - Rotation?

# Advanced Tokamak Status

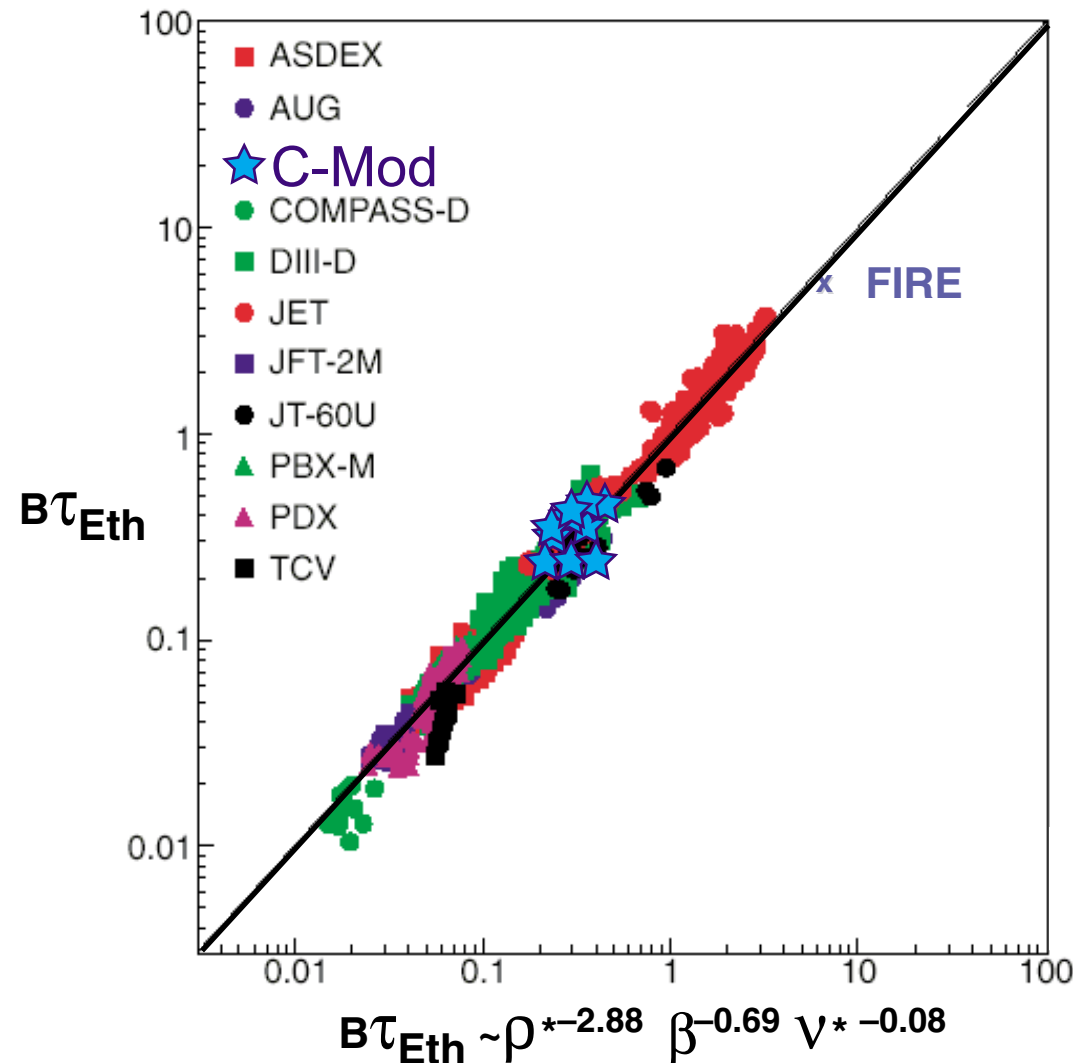


- 
- LHCD Project
    - Well underway; first experiments March 2003
  - Transport-driven rotation investigated
  - Density Control
    - Scrape-off layer particle transport characterized
    - Low  $n_e$  H-modes under study
    - ICRF “control” of density profile discovered
  - Confinement
    - ITB with EDA H-Mode edge
    - 2 freq. ICRF
      - Maintain peaked  $n$ , heat on-axis
      - Density unperturbed outside barrier (good target for LHCD)

# Compact, High Field



- Broaden the physics basis for compact, high field, next step burning plasma options
- Science issues
  - H-Mode threshold and pedestal physics
  - Heating at high density
  - Density and density profile control; Density limits
    - strongest parameters affecting fusion power
  - Divertor physics and Power handling
  - Impurity control
  - Disruptions
  - Confinement scaling

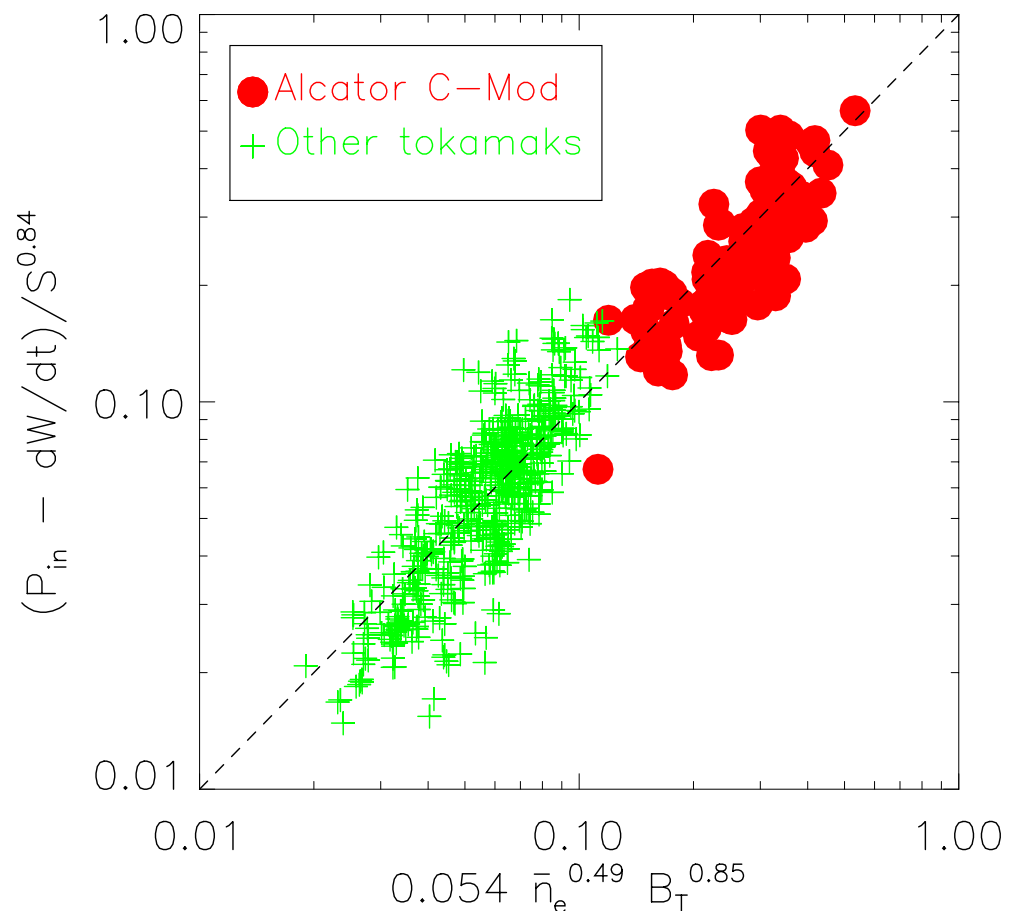


# Compact, High Field Studies Status



- H-mode threshold well studied
  - parameter range extended significantly
- ICRF heating works well at high density
  - antenna-plasma interactions and impurity control still under investigation
- ITBs studied
  - no core fueling
  - Density profile control
  - Enhanced confinement
- Density limit physics understanding increasing

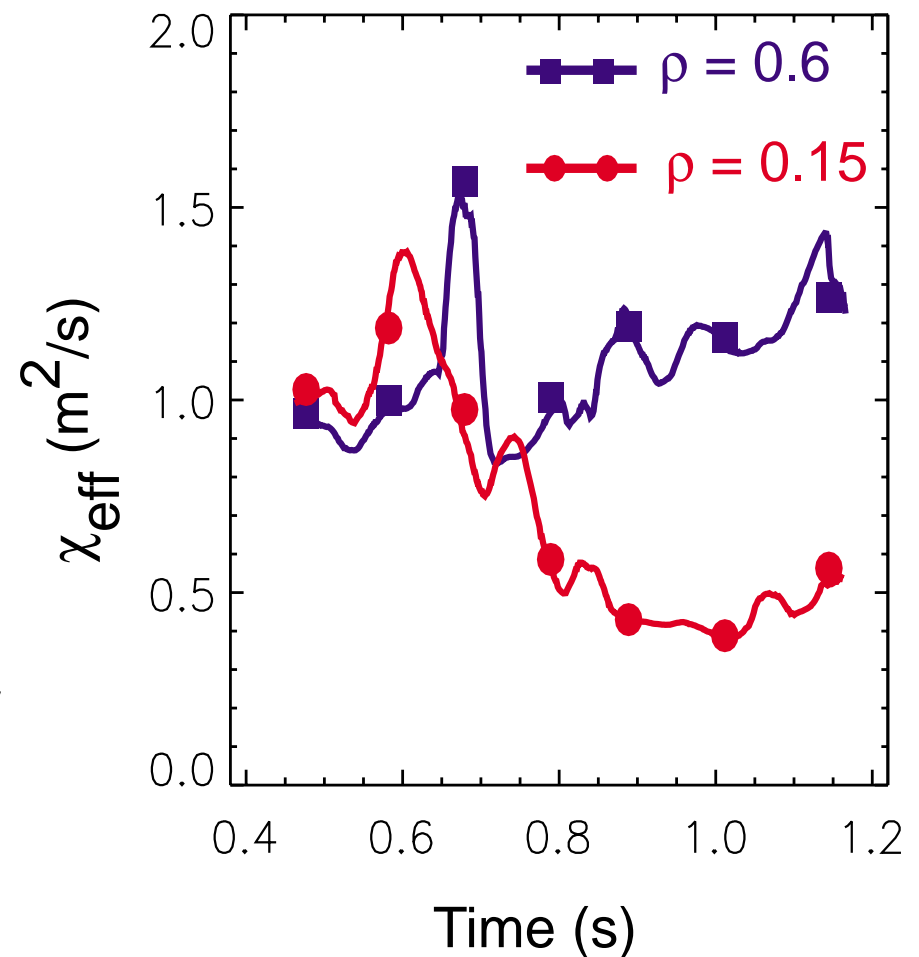
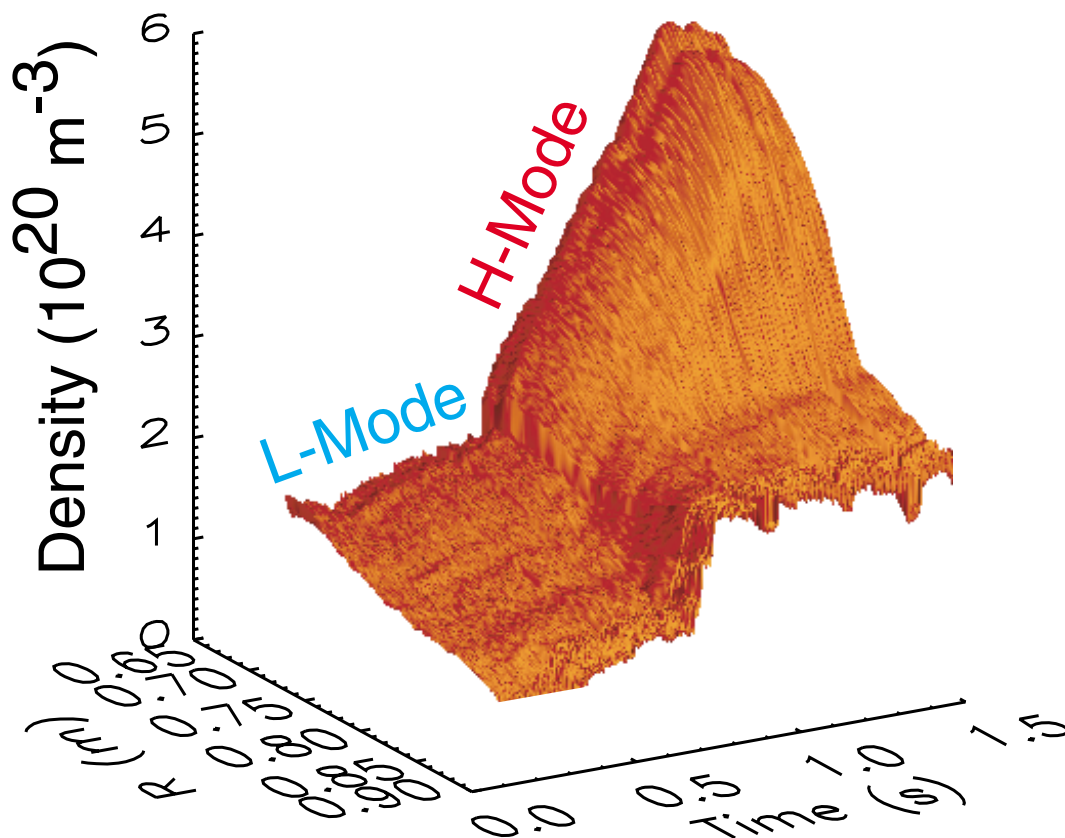
C-Mod Extends the H-Mode Threshold Database by about 1 Order of Magnitude in Power/Surface Area



# TRANSP Analysis Shows Formation of Energy Transport Barrier

2 frequency ICRF:

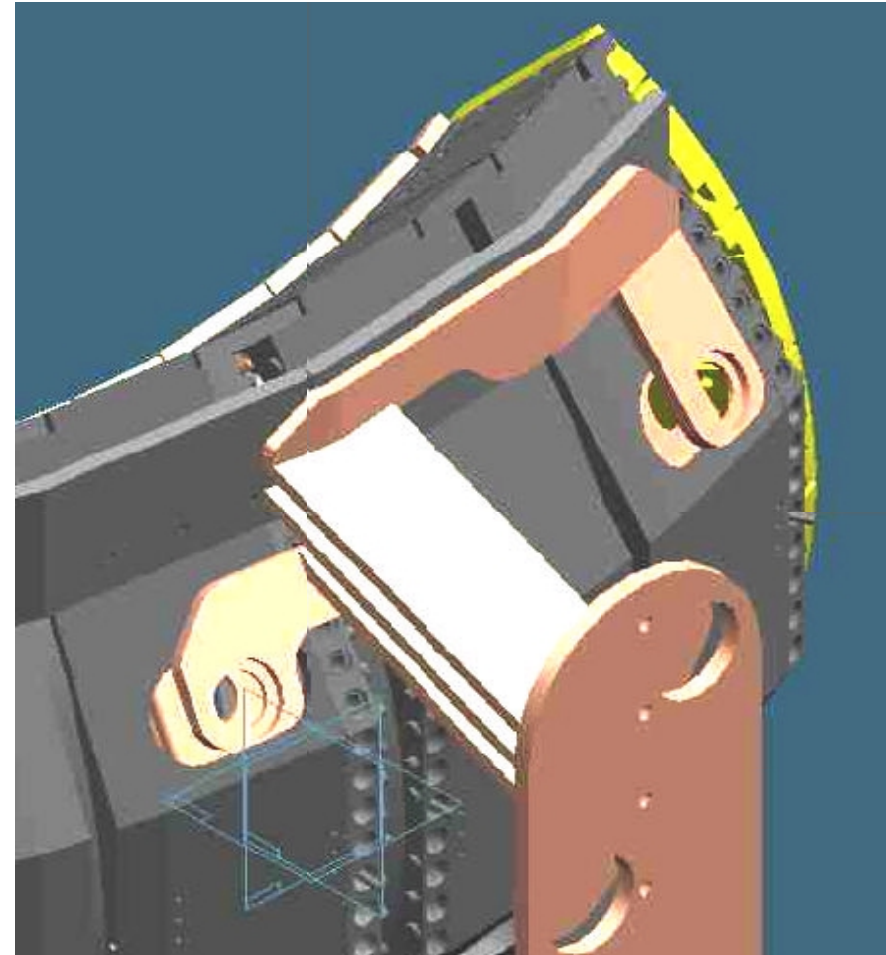
Off-axis triggers ITB; on-axis heats and arrests density (& impurity) buildup



# Priorities for Spring 2001 Campaign



- ICRF
  - Evaluate modifications to J-Port antenna
  - More heating power
    - Higher  $\beta$ , Stronger ITB core heating ( $\geq 3$  MW)
    - EDA/ELM physics
  - First experiments on MC flow drive
- Evaluation of long pulse operation
- Diagnostic Neutral Beam
  - Evaluation of beam and diagnostic (MSE, CXRS, BES) improvements
  - Physics measurements ( $T_i$ ,  $v_\phi$  profiles)
- Additional work on critical physics tasks from CY2000





# Spring 2001 Operation

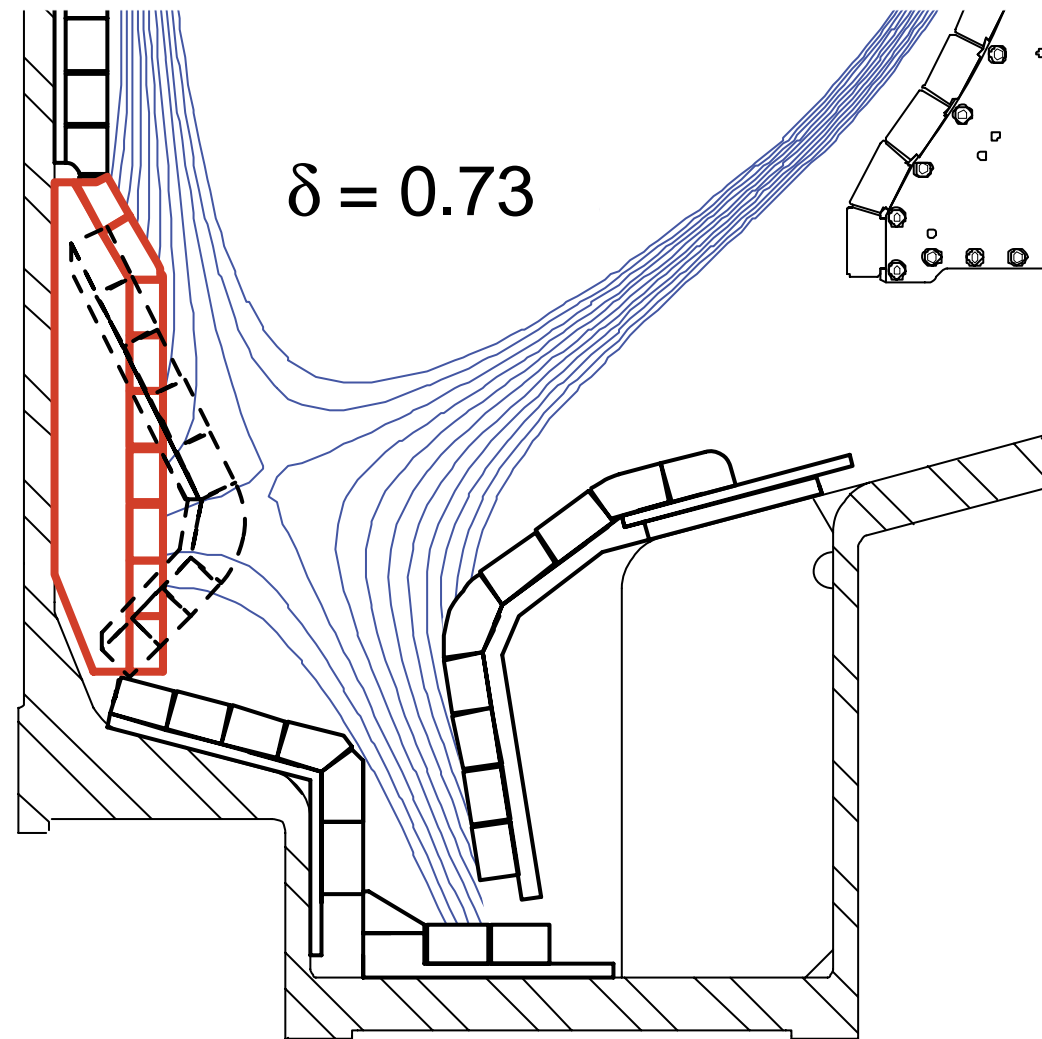


- Extend  $P_{\text{tot}} > 5 \text{ MW}$ 
  - Increase  $\beta_N > 1.7$
  - Scrape-off power,  $P_{\parallel} > 500 \text{ MW/m}^2$
  - Confinement scaling
- Further investigations of 2 frequency ICRF
  - prolonged control of density peaking
  - identify mechanism(s)
  - Increased on-axis heating (  $\geq 3 \text{ MW}$  )

# Modifications/Upgrades Prior to FY2002 Campaign



- Inner wall modifications
  - Increase shape (triangularity) flexibility
  - Operation to 2 MA
  - Upgraded halo and eddy current disruption diagnostics
- DNB/Diagnostics
  - Evaluate ultimate capabilities of present beam
  - Consider upgrade paths (long pulse)
- Adding active MHD coils

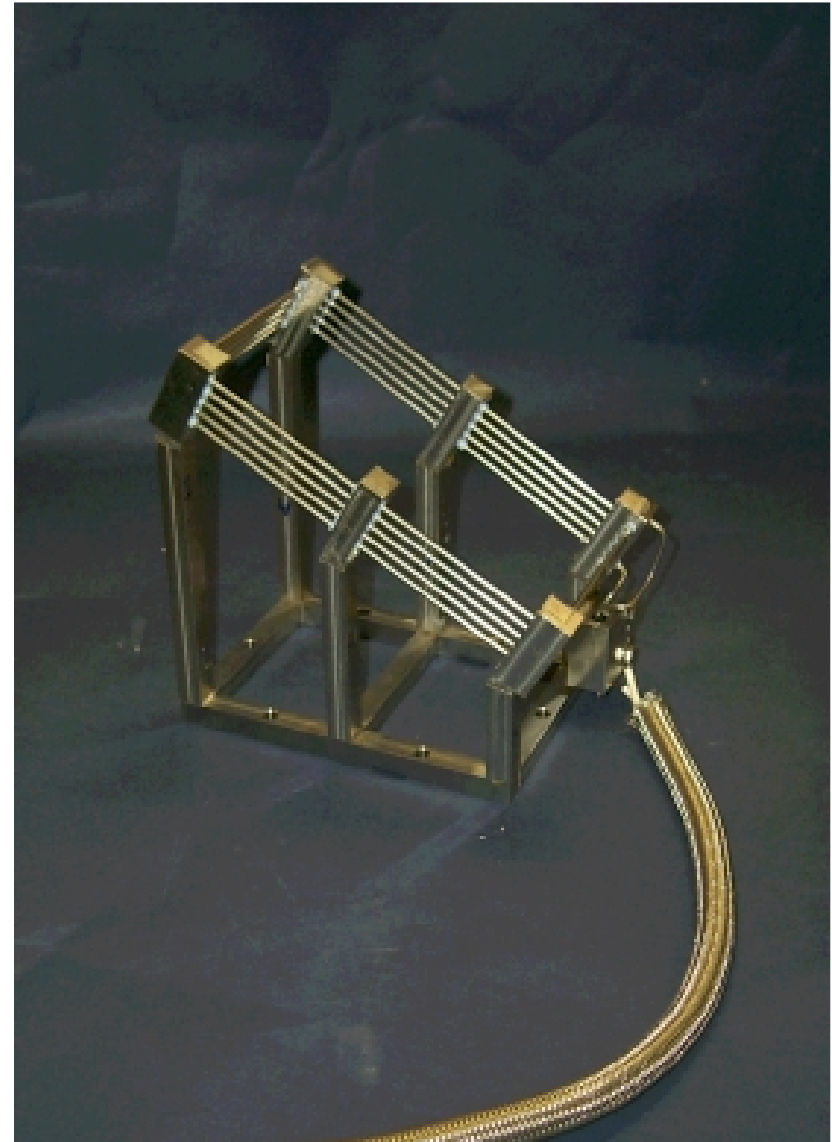




# Priorities for FY2002 Campaign



- Exploit new capabilities
  - 2 MA at 8 Tesla
  - Increased shaping flexibility
  - Active MHD coils
- ICRF current and flow drive
  - 2 frequency ITB physics
- Extend long pulse investigations
- Density control
- Dissipative divertor
- Disruption mitigation
- EDA/ELM investigations



# Modifications/Upgrades prior to FY2003 Campaign

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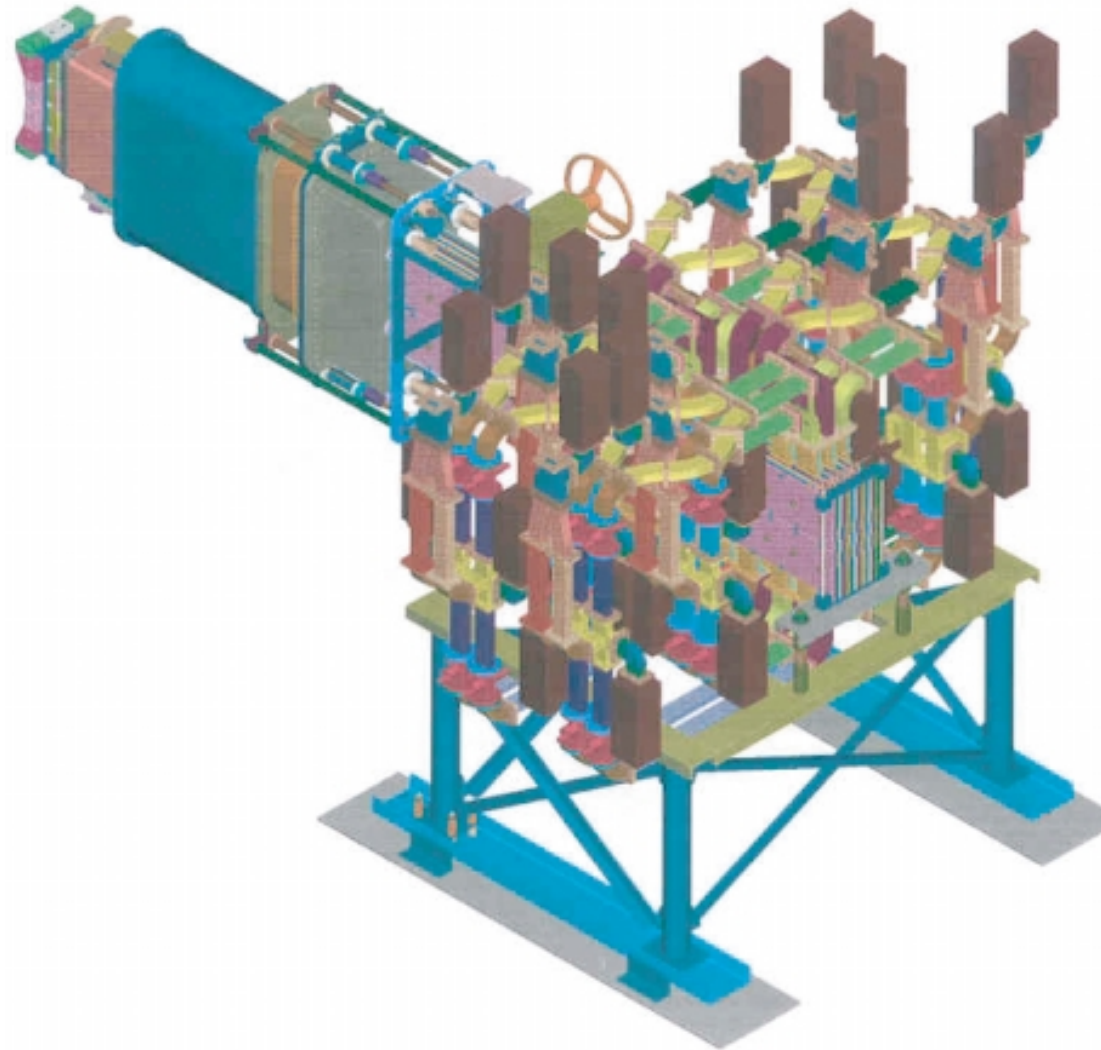


- Under Guidance (A) budgets:
  - Install first lower hybrid launcher
  - 3 MW klystron source power operational
- With Incremental (B) Budgets:
  - Divertor cryopump for density control
  - High energy X-ray imaging (fast electron profiles)
  - Start construction of second lower hybrid grill (PPPL)
  - Begin refurbishment of final 4 klystrons, to bring LHCD to total 4 MW capability

# Priorities for FY2003 Campaign

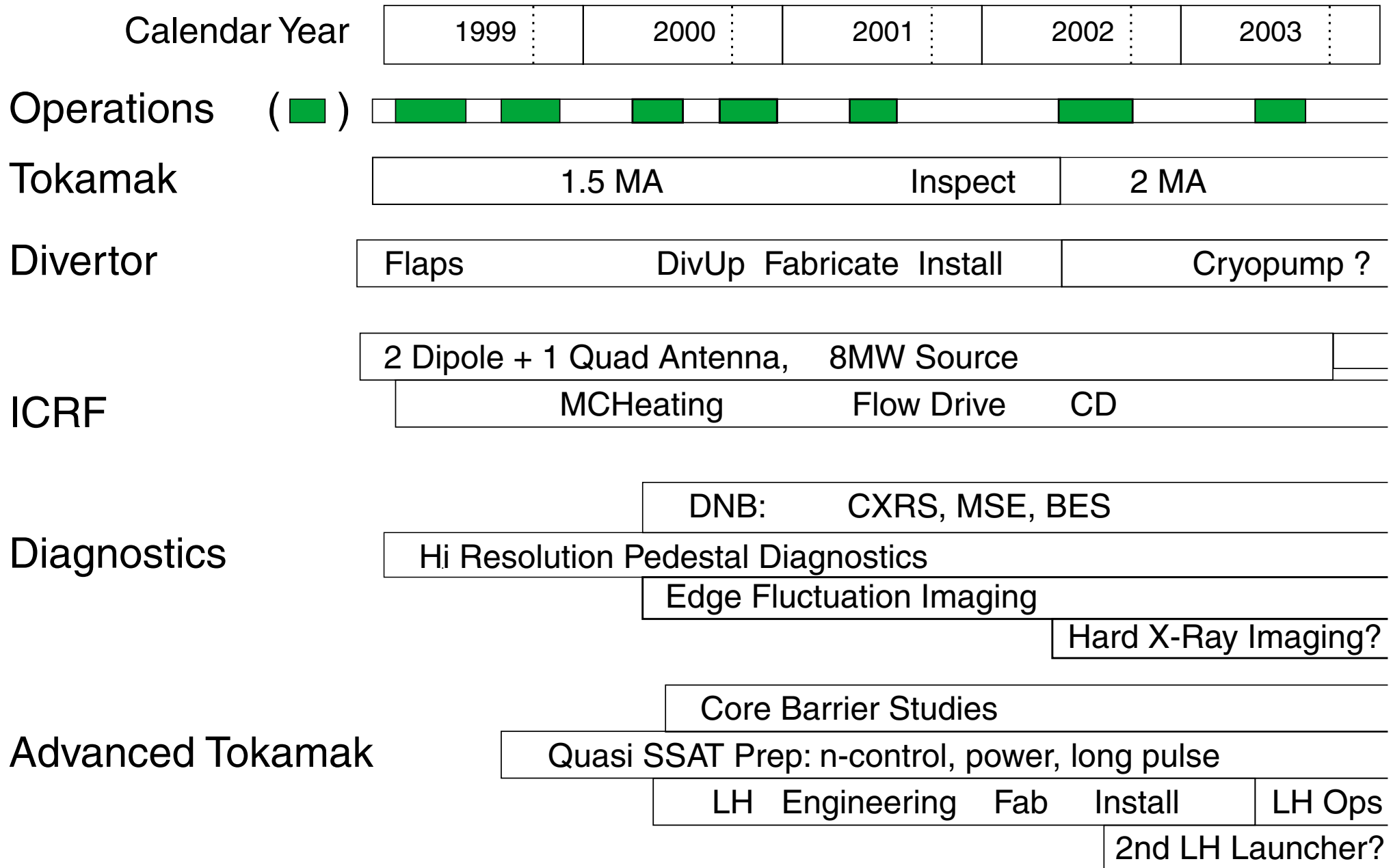


- Assuming flat budgets, combined with increased liquid nitrogen and electricity costs, run time severely constrained (8 weeks for physics)
- Priority will be initial operation of the Phase I Lower Hybrid system (1 launcher, 3 MW source power)



# Alcator C-Mod National Facility

## Overview Schedule (March 2001)



# Milestones



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Measure edge rotation profile with CXRS	JUL 2001
Evaluate operation of modified J-port 4 strap antenna	AUG 2001
Investigation of ITB control with multiple frequency ICRF	AUG 2001
Evaluate integrated H-mode performance, 6 MW ICRF, $I_p \geq 1.2$ MA	AUG 2001
Evaluate density control	AUG 2001
Evaluate mode conversion flow drive	SEP 2001
Complete inner wall modifications	APR 2002
Operate with plasma current of 2 MA	SEP 2002
Evaluate performance at high triangularity	SEP 2002
Evaluate mode conversion current drive	SEP 2002
Measure current density profile with MSE	SEP 2002
Completion of Lower Hybrid Fabrication Project	MAR 2003

# Plain English Goals<sup>\*</sup>



Active formation and control of Internal Transport Barriers	AUG 2001
Plasma probing with energetic neutral particles: Critical measurements	AUG 2001
Plasma flow control with radio waves	SEP 2001
Driving electric current with radio waves	SEP 2002
Higher performance plasmas	SEP 2002
Power and particle handling for Advanced Tokamak plasmas	SEP 2002
Visualization of turbulence	SEP 2002
Commissioning of the microwave current drive system	FY 2003
Current profile control with microwaves	FY 2004

<sup>\*</sup>Details in Work Proposal

# Scientific Personnel



- 
- Over 150 scientists and students involved with the C-Mod Project
    - Includes 21 PhD candidate graduate students, 5 undergraduates and 3 post-doctoral fellows
    - Over 40 institutions (both domestic and international) represented

# C-Mod National Budgets (k\$)

		FY01	FY02A	FY02B	FY03A	FY03B
M I T	Research	4,736	5,096	5,497	4,917	5,639
	Operations	8,291	8,582	9,993	9,091	11,176
	Lower Hybrid	1,347	730	730	400	400
	<b>MIT C-Mod Total</b>	<b>14,374</b>	<b>14,408</b>	<b>16,220</b>	<b>14,408</b>	<b>17,215</b>
	JET Collaborations	55	55	130	55	135
	MDSplus	150	150	150	150	150
	<b>Co-op Agreement Total</b>	<b>14,579</b>	<b>14,613</b>	<b>16,500</b>	<b>14,613</b>	<b>17,500</b>
P P P L	Research	1,237	1,699	1,750	1,675	1,875
	Operations	149	156	357	125	125
	Lower Hybrid	501	500	500	600	1,100
	Equipment	468	0	248	0	0
	<b>PPPL Total</b>	<b>2,355</b>	<b>2,355</b>	<b>2,855</b>	<b>2,400</b>	<b>3,100</b>
U T X	Research	668	668	734	668	760
	Operations	200	200	219	200	227
	Equipment	58	58	64	58	66
	<b>U. Tx. FRC Total</b>	<b>925</b>	<b>925</b>	<b>1,018</b>	<b>925</b>	<b>1,053</b>
	LANL Research	95	95	95	95	95
	<b>Alcator Project Total</b>	<b>17,749</b>	<b>17,783</b>	<b>20,188</b>	<b>17,828</b>	<b>21,463</b>
<b>Grand Total</b>		<b>17,954</b>	<b>17,988</b>	<b>20,468</b>	<b>18,033</b>	<b>21,748</b>



# Infrastructure



- 
- MIT is providing infrastructure upgrades for Lower Hybrid site preparation (\$1,500k) and control room modifications (\$160k)
  - Routine alternator and flywheel inspections required in FY2003
    - Estimated cost is \$830k
    - Puts additional strain on project if budgets are flat

# Facility Run Time is Highly Constrained by Budgets



A Guidance, (B Incremental) Budgets

Fiscal Year	2000	2001	2002	2003
Run Weeks	18	12	10 (14)	8 (18)
Run Hours	600	400	330 (450)	270 (600)

10% Increment in 2002

Fiscal Year	2000	2001	2002	2003
Run Weeks	18	12	12	12
Run Hours	600	400	400	400

10% Decrement in 2002

Fiscal Year	2000	2001	2002	2003
Run Weeks	18	12	8	6
Run Hours	600	400	270	200

# Consequences of 10% Cut (FY2002)



- 
- Personnel layoffs:
    - 2 scientists, 2 engineers, 3 technicians
    - Do not replace 2 PhD students after graduating
  - 8 weeks physics operation
  - Important upgrades, new diagnostics deferred
    - Control system, RF instrumentation, X-pt scanning probe
    - EUV spectrograph, PCI upgrades
    - Replacement of obsolete computer resources
    - Californium source for neutron detector calibration

# Consequences of 10% Cut (FY2003)



- Additional layoffs:
  - 1 scientist, 1 technician
  - 1 additional PhD student not replaced
- Plan for 6 physics weeks
  - Probably schedule at beginning of the fiscal year, to make most efficient use of resources
- Will finish Lower Hybrid Phase I, but defer all other upgrades/new capabilities
  - First operation with Lower Hybrid delayed to FY04
- Loss of one or more important diagnostic systems likely (deferred maintenance, lack of personnel)

# Benefits of 10% Increment



- 
- Increased run time (to 12 physics weeks in FY02 and FY03)
  - Modest staff additions to make better use of campaigns
  - Accomplish highest priority diagnostic & facility upgrades
    - High energy X-ray camera (fast electrons)
    - Divertor cryopump (density control)
    - CXRS spectrometer upgrade (higher resolution poloidal flow)
    - Laser rangefinder (disruption studies)
    - Modest upgrades to ICRF control and matching systems
    - Data acquisition upgrades
    - Replace more of obsolete computing resources
  - Significant increase in JET collaborations
    - Coordinated experiments and MDSplus
  - Start phase II of Lower Hybrid project
    - 2'nd launcher plus refurbishment of remaining klystrons

## Alcator C-MOD Lower Hybrid Project

R. Parker

FY 2003 Budget Planning Meeting

March 13 - 15

Gaithersburg MD

- ARIES studies show the remarkable improvement in the attractiveness of a tokamak reactor that could result from Advanced Tokamak physics operation and advanced technology.
- Key elements of AT operation assumed in ARIES-AT studies such as reversed shear with  $q_{\min} > 2$ ,  $H_H > 1$ ,  $\beta_N \sim 3$  and  $f_{BS} > 50\%$  have been demonstrated transiently in a number of tokamaks. However, such demonstrations have been limited to times less than a current redistribution time.
- By using lower hybrid current drive to supplement the bootstrap current, the potential of AT regimes can be developed and explored in Alcator C-MOD under quasi-steady-state conditions.
- The Lower Hybrid Fabrication Project provides for the installation of 3 MW of RF power at 4.6 GHz with 5 s pulse length in the C-MOD cell, together with an appropriate antenna to couple this power to C-MOD plasmas.

# Alcator C-MOD is Well-Suited for AT Research

- 
- Internal PF coils provide strong shaping required to access high  $\beta_n$  and  $\beta_p$  (and therefore high bootstrap current) regimes.
  - Relatively small major radius means high net efficiency for current drive,  $I_{CD}/P$ .
  - Pulse length of 5 sec @ 5 T is comparable to the L/R time ( $T \sim 5$  keV), an important time scale for reaching fully steady-state conditions. C-MOD is the only shaped tokamak presently with this capability.
  - The installed ICRH capability of 6 MW is sufficient to reach high  $\beta_n$ . Variable frequency antenna allows flexibility in power deposition profile and some control of pressure profile.



# Lower Hybrid Current Drive is a Good Fit to Alcator C-MOD

- Lower hybrid has proven current drive capability. The current drive efficiency is highest of any current drive method.
- Current deposition profile is consistent with reversed shear scenarios, e.g., in ARIES-RS.
- Grill phasing permits dynamic control of  $n_{||}$ , which varies driven current deposition profile.
- Extensive experience with lower hybrid current drive systems at the PSFC, beginning with Alcator A, then Versator and Alcator C. PSFC experience is complemented by that of PPPL collaborators from PLT and PBX-M LH experiments.
- Reuse of equipment from the Alcator C LH experiment results in a highly cost effective fabrication.

**Purpose:** To develop and explore the potential of Advanced Tokamak regimes, i.e., regimes with high bootstrap fraction ( $\sim 70\%$ ), high  $\beta_n$  ( $\sim 3$ ) and high confinement ( $H_H \sim 1-2$ ) in Alcator C-MOD under quasi-steady-state conditions,  $T_{\text{pulse}} \sim 5 \text{ s} \geq L/R$ .

**Tools:** The main tools for these experiments will be a 4 MW Lower Hybrid RF system (New Fabrication) and 6 MW of ICRF heating (Existing System).

## Ion Cyclotron Heating System

	<i>Phase 1</i> (Present Capability)		<i>Phase 2</i> (upgrade)
	Antenna 1&2	Antenna 3	Antenna 1&2
<b>Frequency</b>	<b>80 MHz</b>	<b>40 – 80 MHz</b>	<b>40 – 80 MHz</b>
<b>Power</b>	<b>2 MW each</b>	<b>4 MW</b>	<b>4 MW each</b>
<b>Antenna</b>	<b>2 Straps</b>	<b>4 Straps</b>	<b>4 Straps</b>

## Lower Hybrid Current Drive System

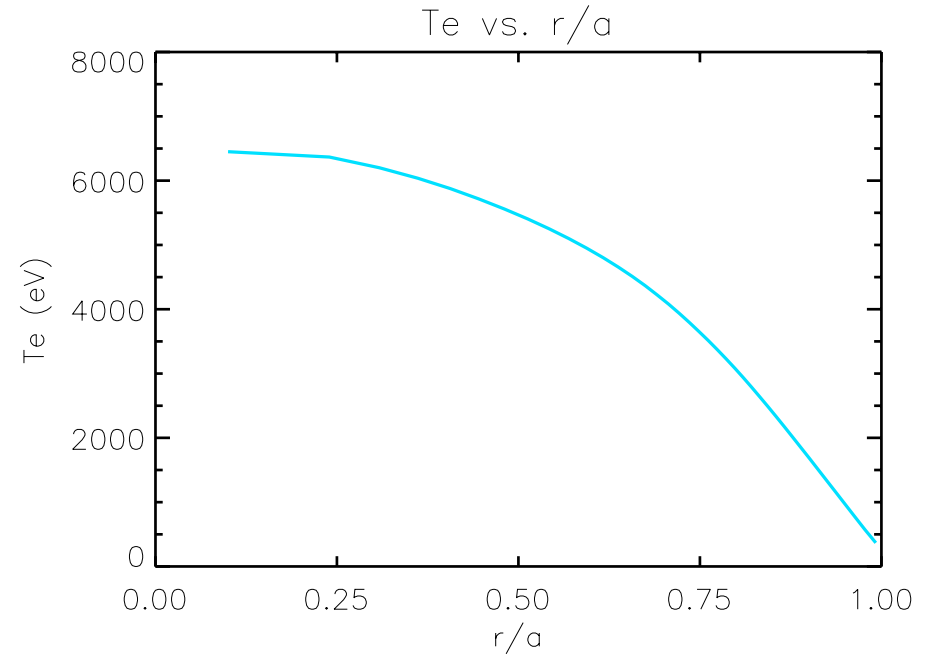
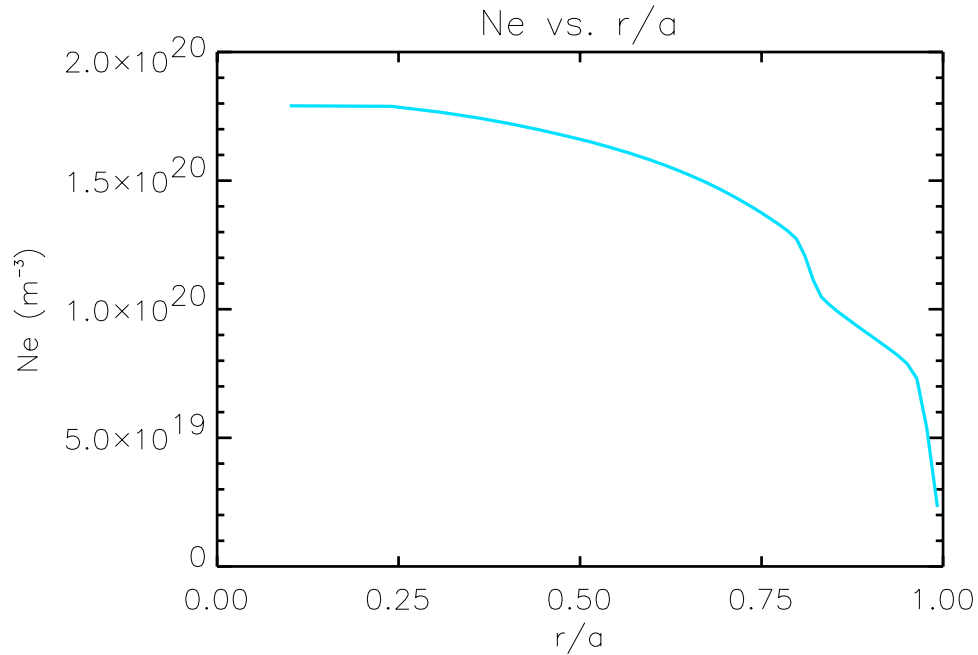
	<i>Phase 1</i>	<i>Phase 2</i>
<b>Frequency</b>	<b>4.6 GHz</b>	<b>4.6 GHz</b>
<b>Power</b>	<b>3 MW</b>	<b>4 MW</b>
<b>Antenna</b>	<b>4X24 Waveguide Grill (1)</b>	<b>4X24 Waveguide Grills (2)</b>
<b><math>N_{  }</math> (Variable)</b>	<b>2-3</b>	<b>2-3</b>

# Modelling Studies Show the Basis for Steady State LH Driven AT Regimes in C-MOD

- Modeling studies by Bonoli, Ramos and Porkolab have established the basis for using LHCD to produce steady-state AT Regimes in Alcator C-MOD.
- The current density profiles developed in the modeling are in line with those assumed in the ARIES AT studies. However, a key issue is the stabilization of the  $n = 1$  resistive wall mode. Without feedback stabilization, maximum  $\beta_N < 3$ . This is a generic tokamak issue!
- Somewhat serendipitously, a double transport barrier similar to that assumed in the density profile used in the modeling studies have been produced in C-MOD with off-axis ( $R < R_{\text{mag}}$ ) ICRF heating.
- Although densities are somewhat higher than in the model, significant current drive is still possible with 2 MW of coupled lower hybrid power.

# Plasma Profiles for Double Barrier Formation Near the $\beta$ -limit

$$n_e(0) = 1.8 \times 10^{20} \text{ m}^{-3} \quad T_e(0) = 6.45 \text{ keV} \quad B_0 = 4.0 \text{ T}$$



$$p(\psi) = n(\psi)T(\psi)$$

$$T(\psi) = T(0)[0.7(1-\psi)^{3/2} + 0.3(1-\psi^4)]$$

$$n(\psi) = n(0)[(1-\psi) + \Delta n_I(\psi) + \Delta n_E(\psi)]$$

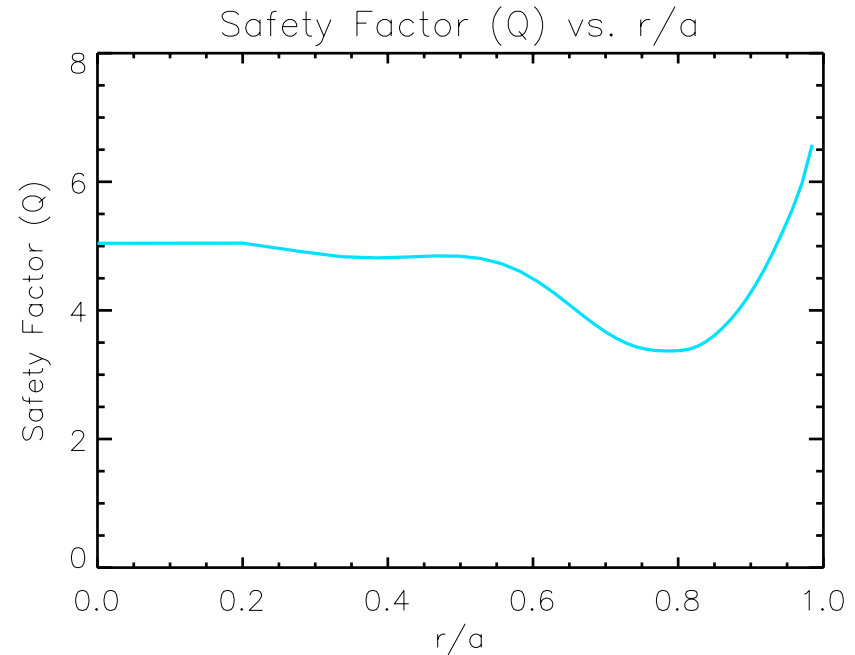
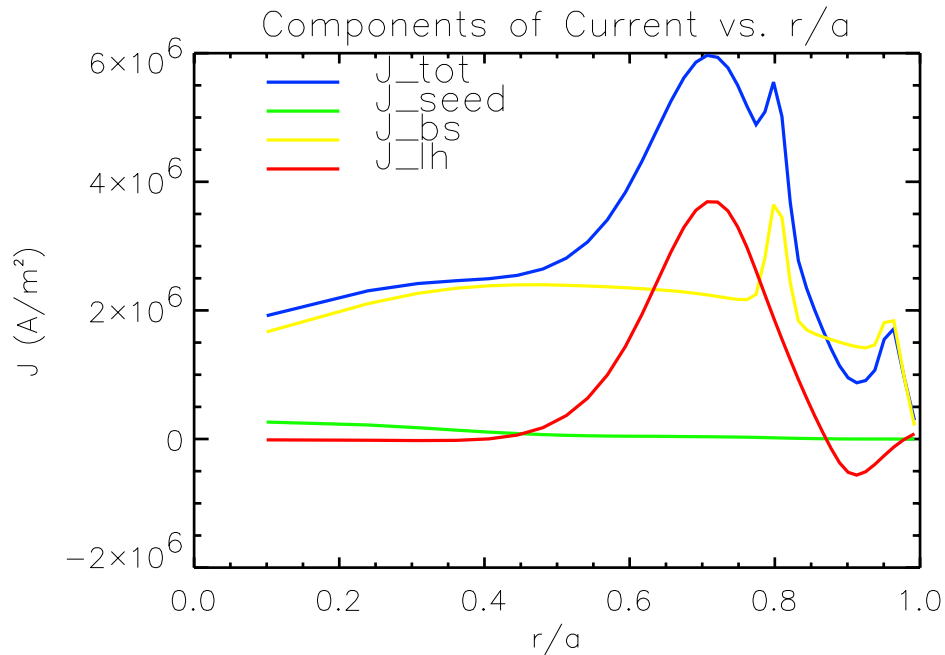
$$H_{\text{ITER-89}} \simeq 2.5$$

$$P_{\text{ICRF}} \simeq 5.0 \text{ MW}$$



# Double Barrier Formation Near the $\beta$ -limit ( $B_0 = 4.0$ T, $\beta_N = 2.72$ )

$$n_e(0) = 1.8 \times 10^{20} \text{ m}^{-3}, \quad T_e(0) = 6.45 \text{ keV}, \quad P_{\text{ICRF}} \simeq 5.0 \text{ MW}$$



$$I_p = 0.88 \text{ MA} \quad f_{\text{BS}} = 0.68$$

$$I_{\text{LH}} = 0.27 \text{ MA}$$

$$P_{\text{LH}} = 3.0 \text{ MW} \quad (n_{\parallel}^0 = 3.00)$$

Stable to  $n = 1$  mode

Unstable to  $n = \infty \rightarrow 0.88 \lesssim r/a \lesssim 0.94$

$$q_0 = 4.99 \quad q_{\text{min}} = 3.37$$

$$\beta_t = 2.60\%$$

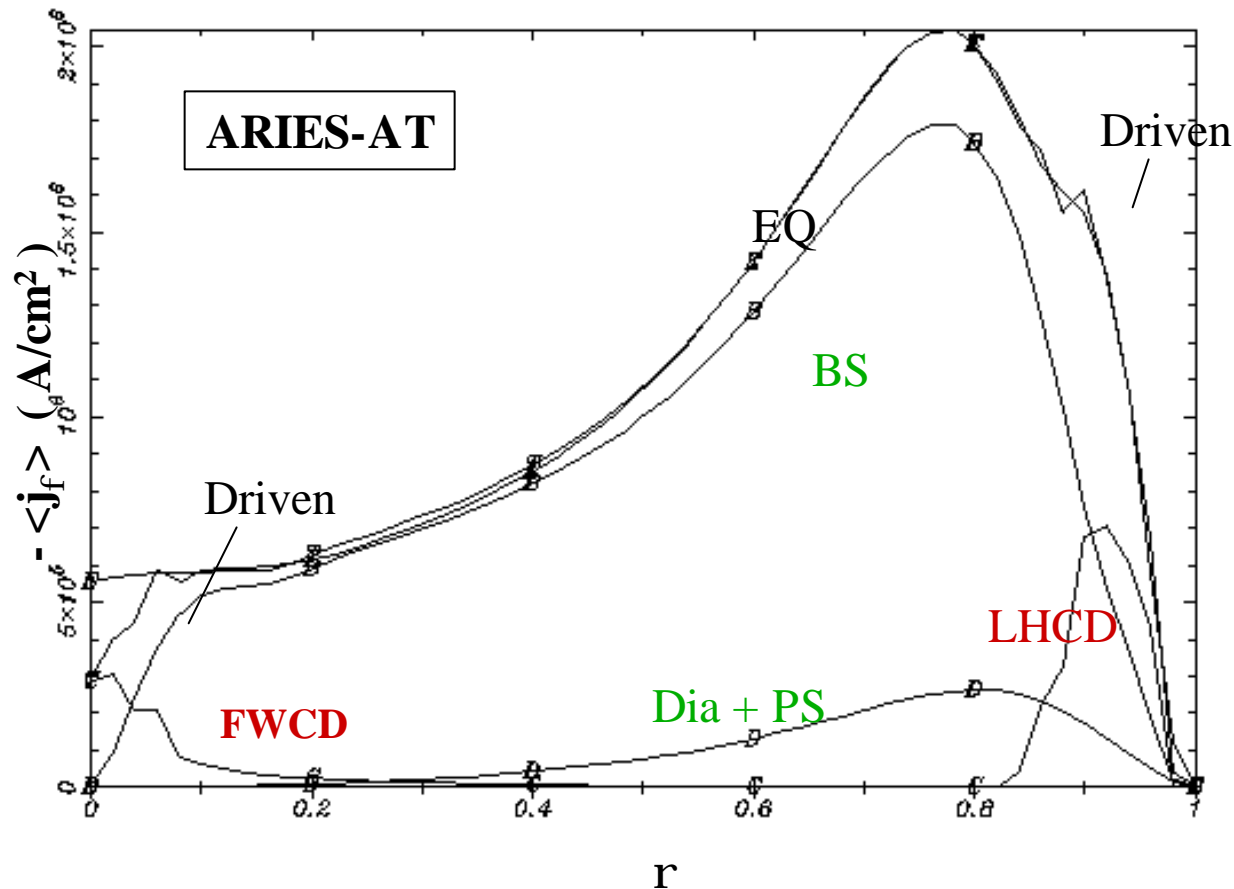
$$p(0)/\langle p \rangle = 2.15$$



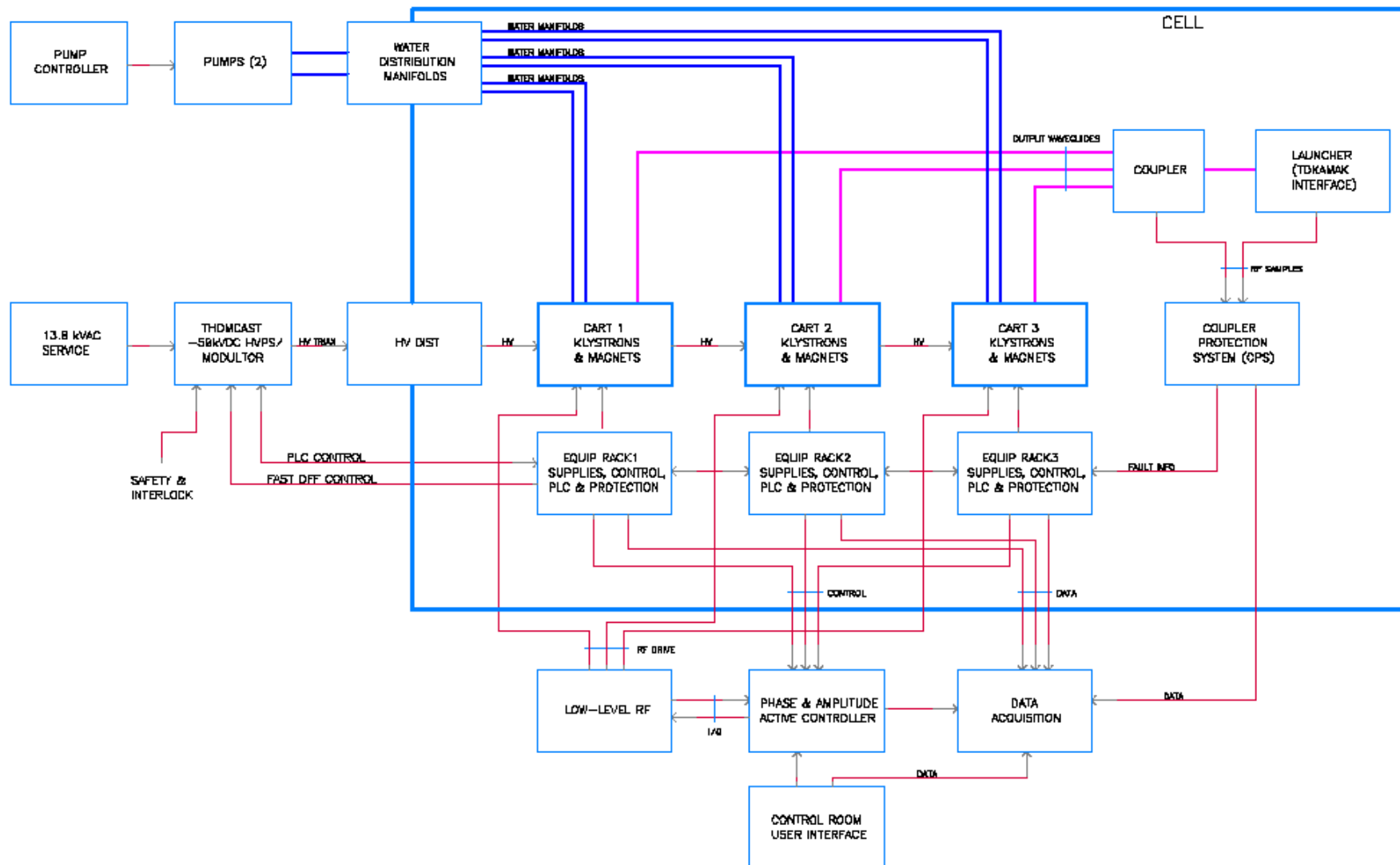
# Target Equilibrium Can be Maintained with RF- and Self-Driven Currents

ARIES  
PULSAR  
STARLITE

- **2 RF schemes** are required to drive the seed currents on ARIES-AT:  
(1) ICRF fast waves for on-axis drive; (2) LH waves for off-axis drive.



## LOWER HYBRID BLOCK DIAGRAM





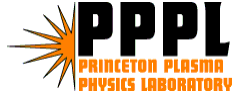
## Excellent Progress Has Been Made During Past Year on RF System Design and Development

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- The 16 klystrons returned to MIT after sojourns in PPPL and LLNL have been tested to  $\geq 250$  kW for 10 msec; 14 were found suitable for Phase I use (12 needed). The two remaining klystrons will require filament replacement.
- Three of the four carts supporting 4 klystrons each and used in Alcator C LH experiments have been refurbished and are nearly ready for installation in C-MOD cell.
- Contracts for the two large procurements, the power supply/modulator and isolators have been let. The vendors are well qualified and timely deliveries are expected.
- Design for a dynamic control amplitude and phase control system has been completed and the performance of a prototype is being evaluated.
- Development of a CPCI data acquisition system, which replaces CAMAC and which has broad application in the fusion community. Contract for 400 channel system with 1 Msample/channel (16 Bits) @ 250 kHz bandwidth has been placed.





## PPPL is Has Also Made Excellent Progress on Coupler Design and R&D

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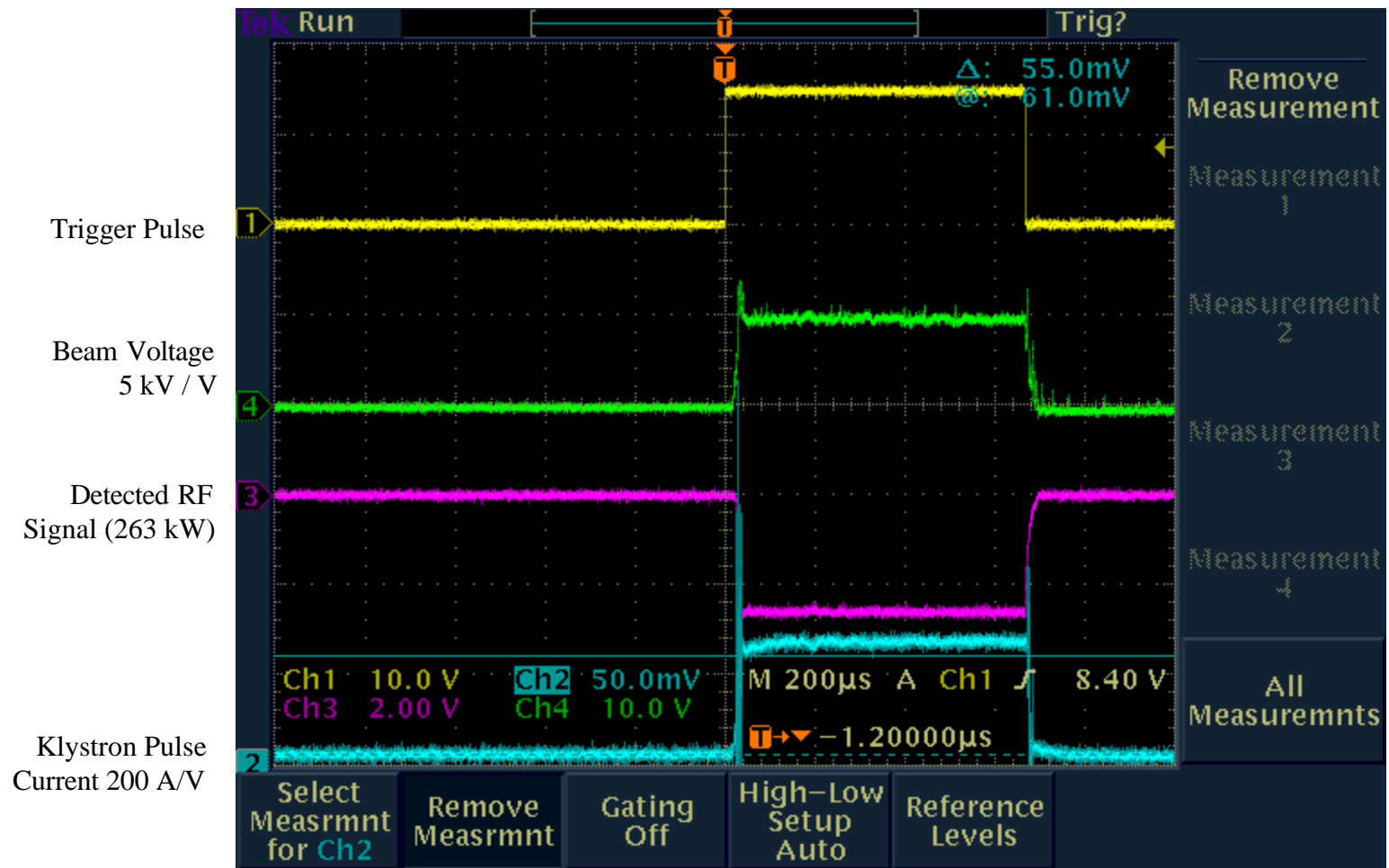


- Both Conceptual and Preliminary Design Reviews have been completed
- Two prototype 3-waveguide Couplers have been fabricated and are being used to:
  - Qualify machine shops for final manufacture
  - Investigate tolerance and flatness issues
  - Check coupler to stacked waveguide gasket fabrication
  - Evaluate Coupler losses and splitter performance
  - Evaluate taper to standard waveguide performance
  - Test and evaluate ceramic window brazing and performance

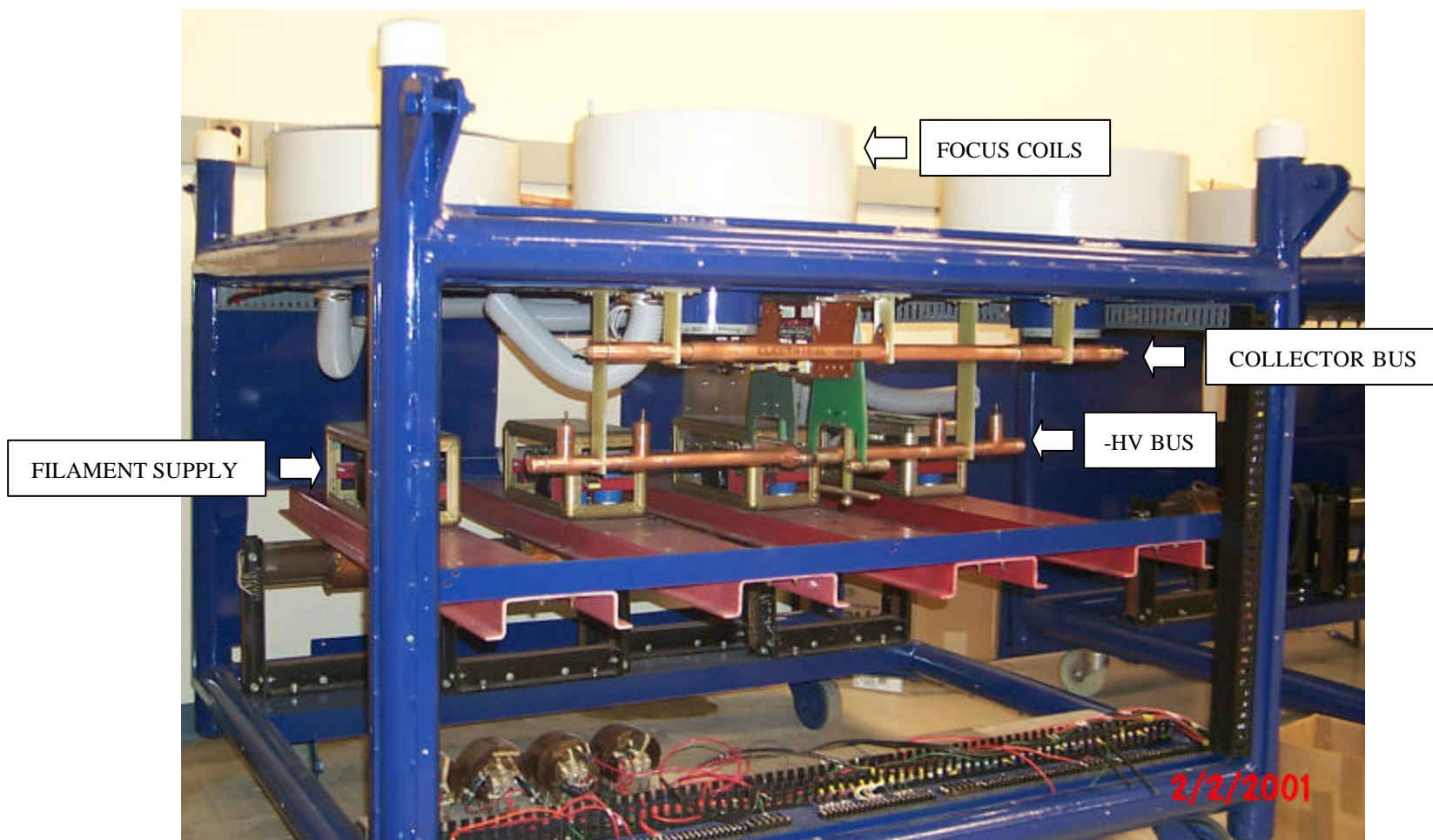
## RF System - Klystrons



# RF System – Klystron Test Data



## RF System – Klystron Carts



# High-Voltage Power Supply/Modulator

## Key Specifications:

Output Voltage – 0 to -50 kV Regulated, Adjustable

Output Current – 0 to 208 A Adjustable Trip Point

Pulse Width – 5 Seconds

Duty Cycle – 0.5 % Max.

Flatness –  $\pm 1/2$  %

Over/Undershoot – 2%

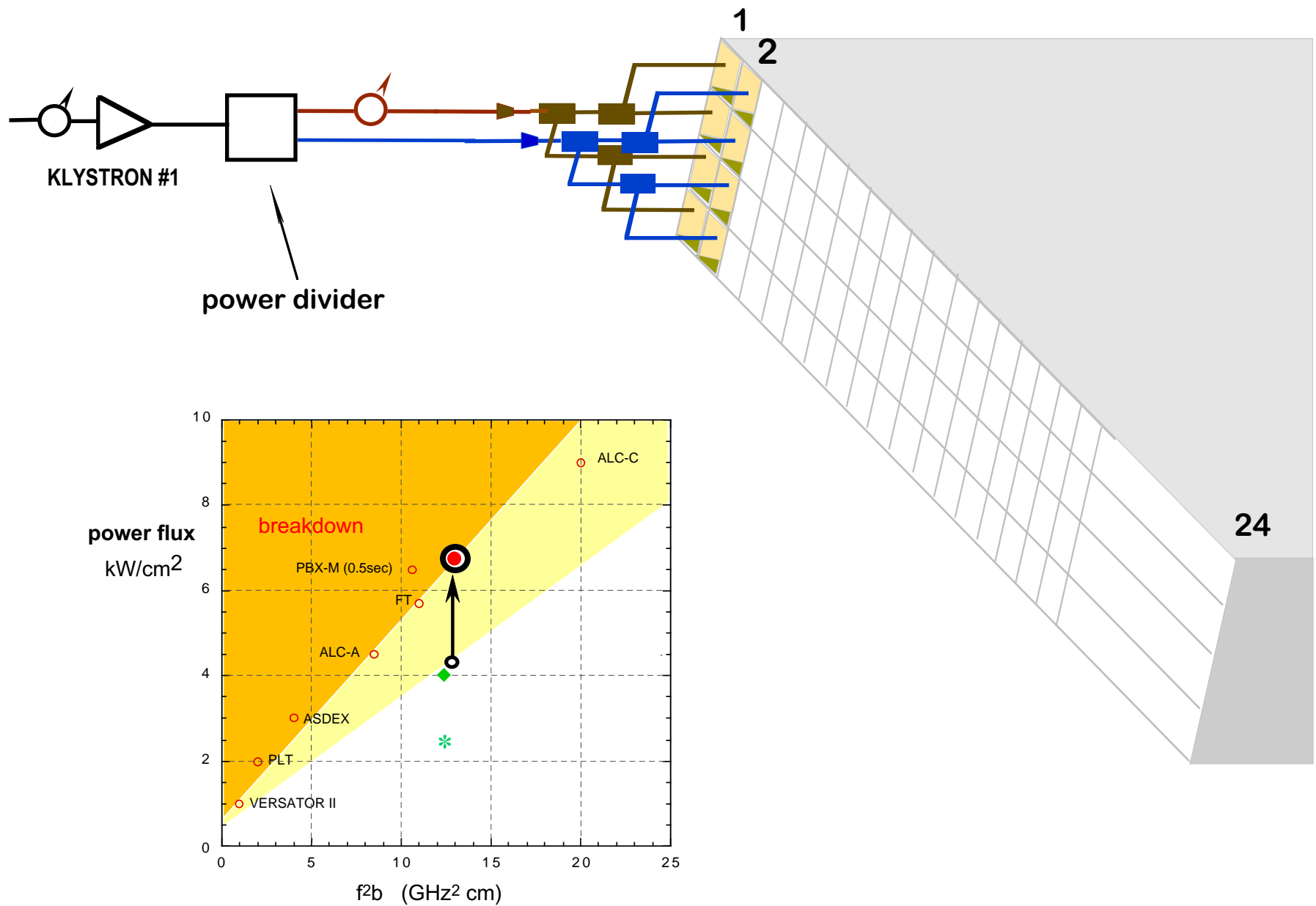
Rise/Fall Time – 50  $\mu$ s Adjustable, for Normal Operation

Fall Time for Fault – 3  $\mu$ s or Less

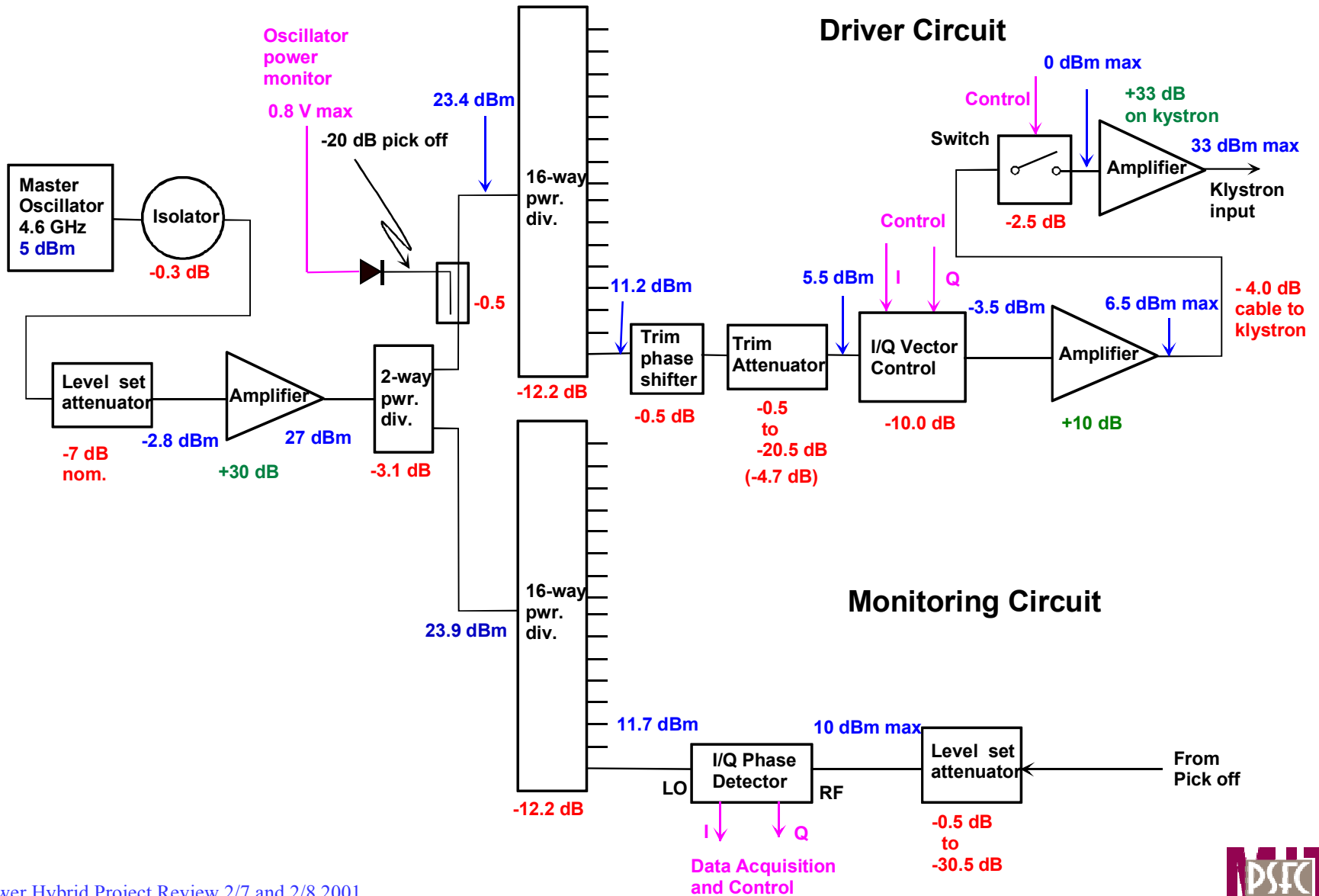
Line Voltage – 13.8 kV AC, 60 Hz, 3-phase

PLC Interface – Set Points and Status via Fiber-Optic Link

## 1<sup>st</sup> PHASE: 12 KLYSTRONS ON TO ONE COUPLER

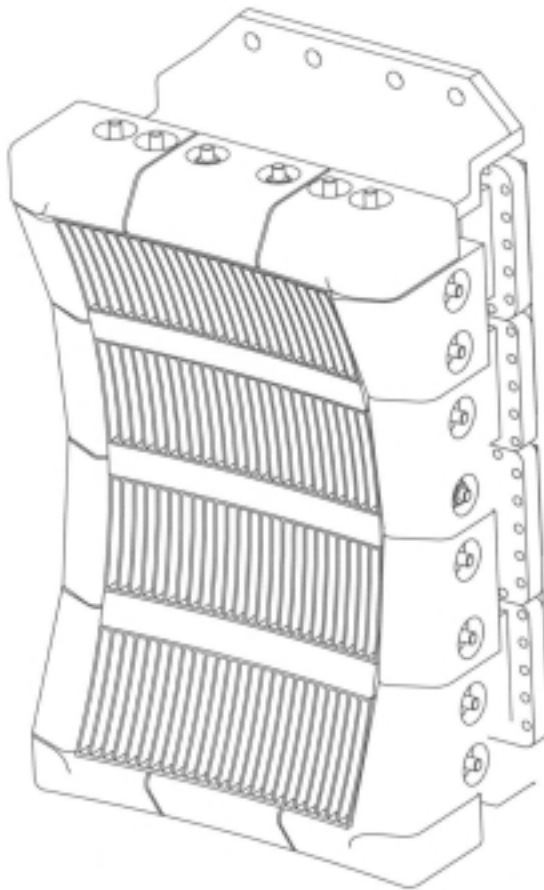


# Low Power LHCD Circuit Details





# Coupler

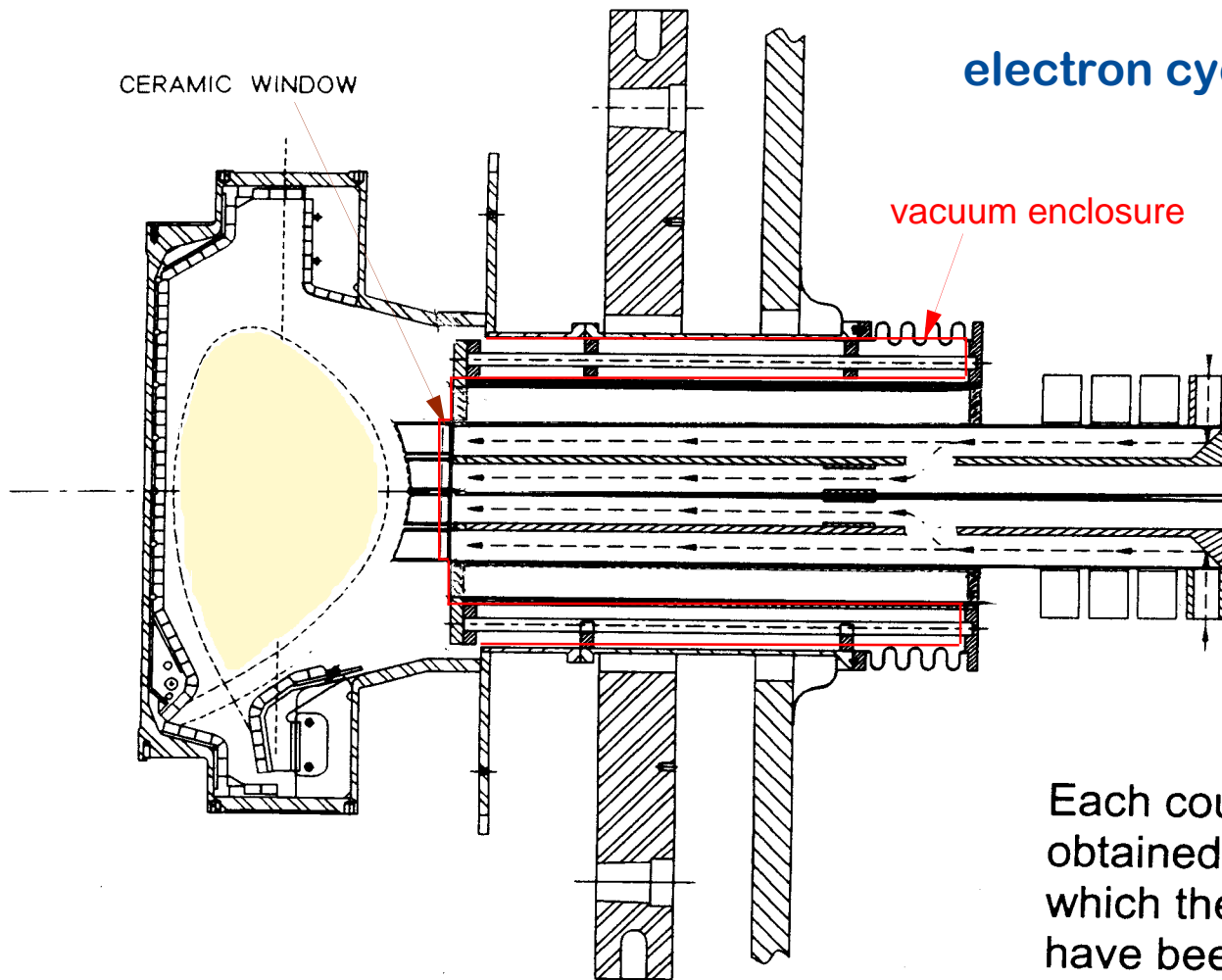


- 24 waveguides X 4 modules
- Each channel waveguide vacuum sealed with  $\text{Al}_2\text{O}_3$  ceramic brick
- Bricks will be coated and then brazed into the waveguide
- Module is then vacuum sealed to the rest of the launcher with a 0.03" gold seal
- TCs monitor temps



no waveguide joint in vacuum.

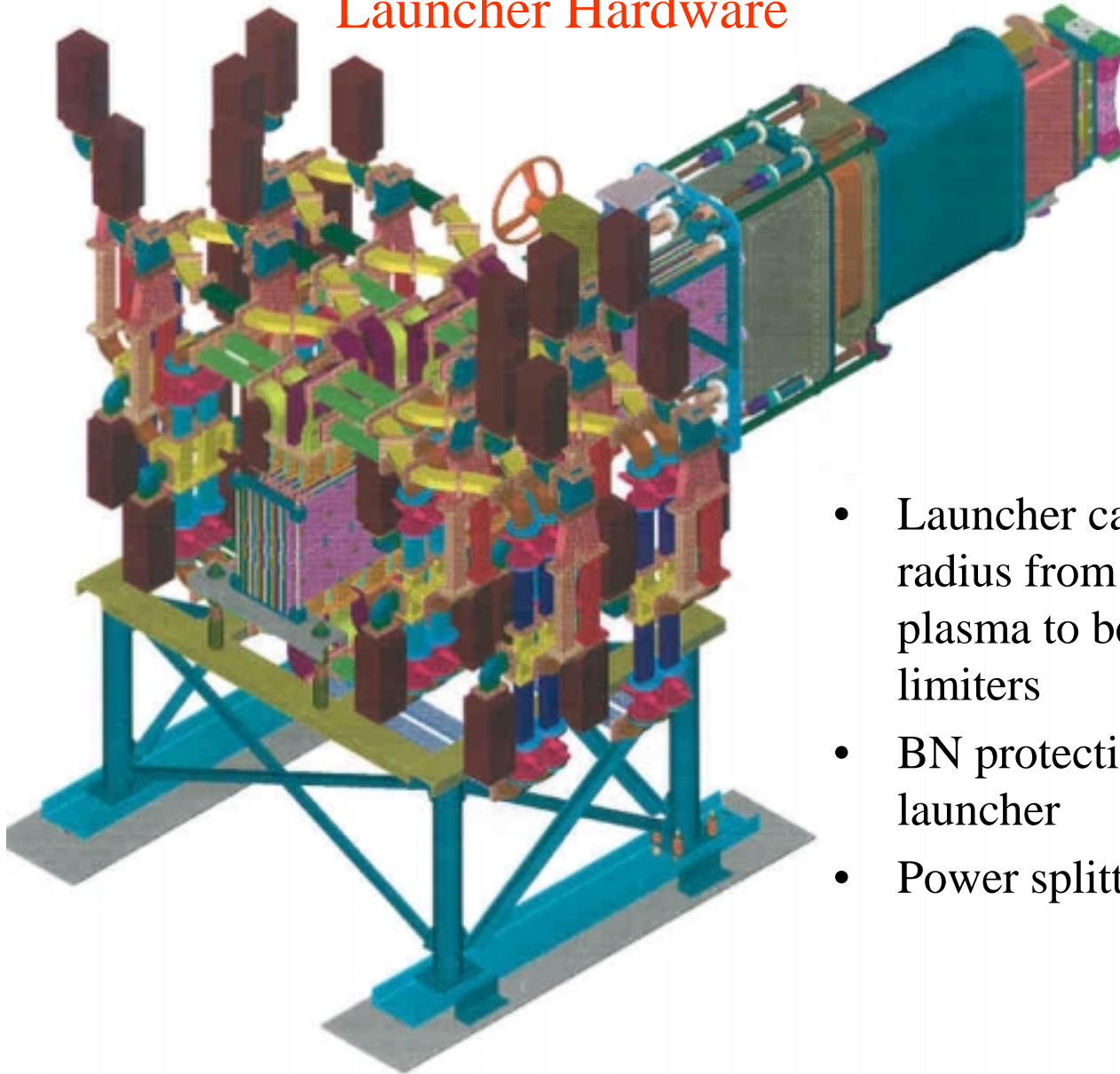
electron cyclotron layer in air side.



Each couple of adjacent arrays is obtained by stacking 24 plates on which the waveguides channels have been milled

SECTION ELEVATION  
THRU MACHINE/ANTENNA

## Launcher Hardware

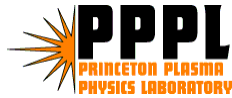


- Launcher can be moved in major radius from approx 0.5 cm from the plasma to behind other machine limiters
- BN protection tiles move with the launcher
- Power splitters built into launcher

- The project was approved in February 2000 with a completion target date of August 2002 (30 months) and an estimated cost of 4.2 M\$ without contingency.
- After completion of the pre-conceptual design last summer, the project baseline budget was established at 5.2 M\$ which remains the present projected cost. The funding profile is shown in the Table:

	<i><b>FY 00</b></i>	<i><b>FY 01</b></i>	<i><b>FY 02</b></i>	<i><b>FY 03</b></i>
<b>Budget Profile</b>				
<b>PSFC</b>	820	1350	730	400
<b>PPPL</b>	300	500	500	600
<b>Total</b>	1120	1850	1230	1000
<b>Project Total</b>	5200 (k\$)			

- The budget profile causes a delay in the original completion date. With the profile shown above, the completion date would be delayed 6 months beyond the original target date, with experiments beginning in March 2003. Moving FY 03 funds into FY02 would permit completion at the end of FY 02.



# MIT is Making Substantial Contribution to the Lower Hybrid Project



MIT is providing the following:

- Cooling water system for klystrons, including piping, valves, pumps, etc.
- Mezzanine to support klystron carts in C-MOD cell
- Increased low voltage electrical capacity in cell
- Slab for High Voltage Power Supply in Alcator high voltage yard
- Run cabling from HVPS to C-MOD cell
- Run 13.8 service to HVPS
- New setup laboratories

Total value of MIT contributions is approximately \$1.5 M

# Procurements for the RF Power System Are 80 % complete

<b>WBS</b>	<b><i>Baseline Procurements</i></b>	<b><i>Committed to Date</i></b>	<b><i>Remaining</i></b>
<b>2. AC-DC Power Conversion</b>	1208	1208	
<b>3. Klystron Cooling System</b>	49 <sup>1</sup>		49
<b>4. Low Level RF</b>	90	7.6	82.4
<b>5. Klystrons</b>	138	123	15
<b>6. RF Power Transmission</b>	518	370	148
<b>7. Instrumentation and Ctrl</b>	480	272	108
<b>Totals</b>	2483	1981	402

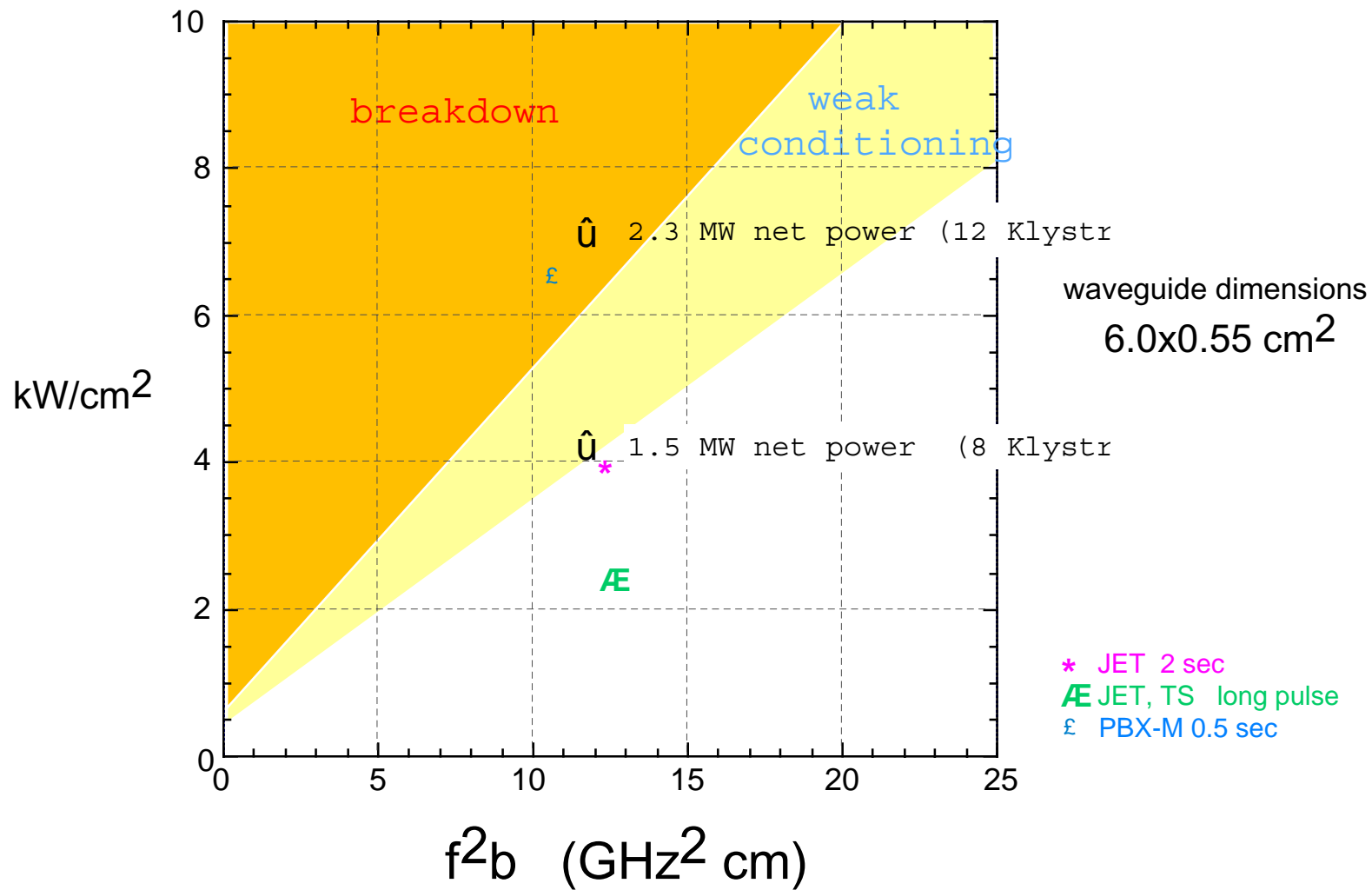
<sup>1</sup>MIT Contribution

## Upgrade of RF Power to 4MW Is Planned for FY 03 (Incremental)

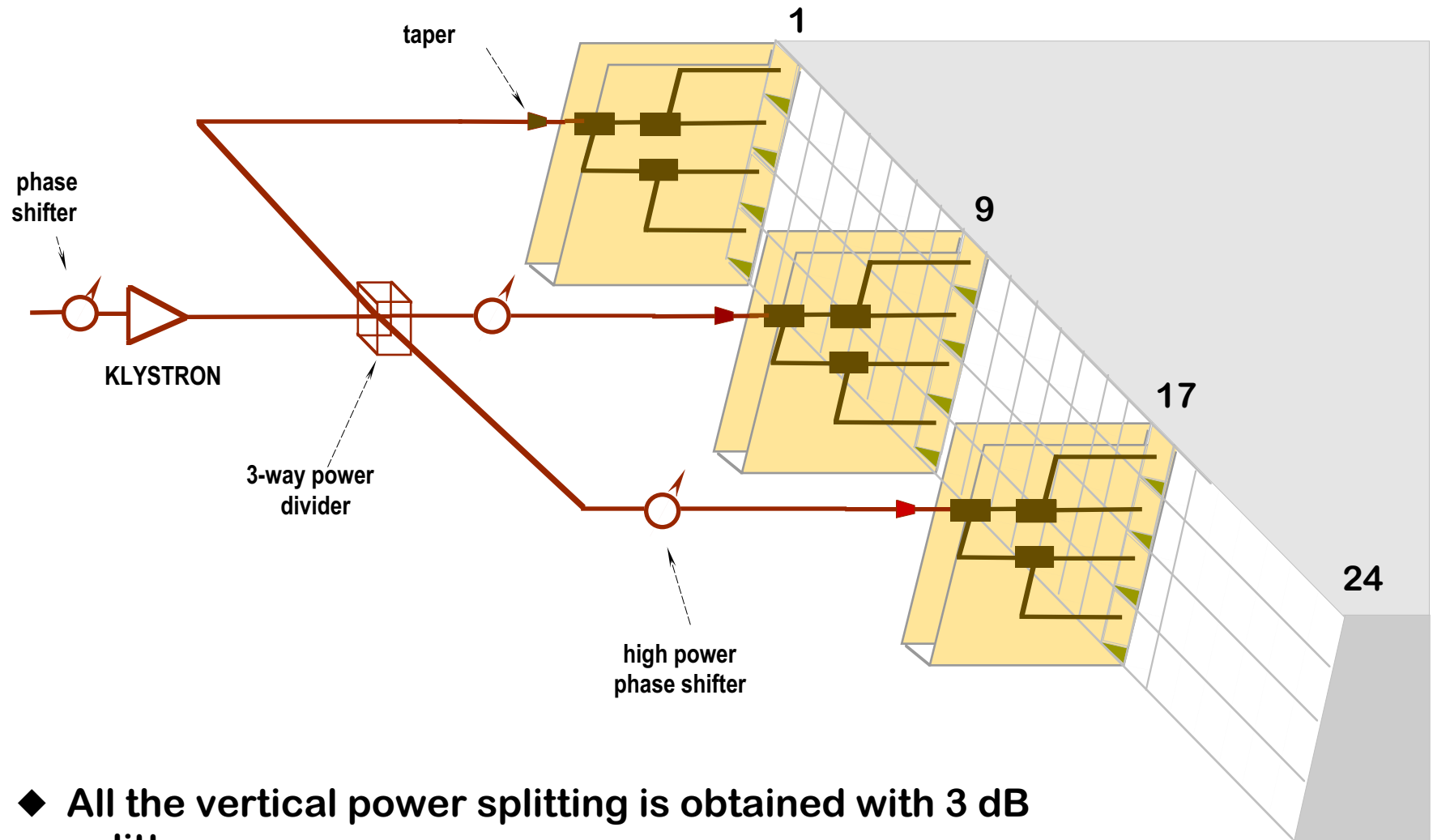
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- A main concern for the success of the lower hybrid experiments is the achievable power density. Empirical scaling suggests that coupling the full Phase I source power of 3 MW is optimistic.
- A Phase II is planned, which would add an additional MW but would also reduce the power density by adding an additional coupler.
- Initiation of the Phase II fabrication in FY 03 is foreseen in the incremental budgets of PSFC and PPPL.

# power flux in the waveguides



## COMPACT FEED DESIGN



- ◆ All the vertical power splitting is obtained with 3 dB splitters.
- ◆ All the remaining transmission line is standard size.



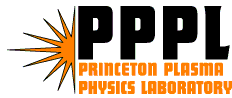
## Lower Hybrid Physics Studies Will Begin in FY 03

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- FY 03 investigations will focus on coupler performance – optimizing RF match to C-MOD plasmas and determining current drive efficiency and ability to control profile.
- Key diagnostics are MSE measurement of total current profile and a new imaging X-Ray spectrometer for evaluating the distribution of lower hybrid driven current. The X-ray spectrometer is proposed to be designed and built in collaboration with Y. Peysson from Tore Supra.
- An important issue of high performance, high  $f_{BS}$ , regimes is the beta limit, which is expected to be due to the onset of resistive wall modes. Active MHD Spectroscopy system, now being installed for use in the next run campaign, will be used to determine both the proximity to RWM's and the feasibility of feedback stabilization.
- Should feedback stabilization show promise, planning for installation of control coils could occur in FY03.

# Lower Hybrid Experiments on C-MOD Will Make Substantial Contribution to IPPA Goals

IPPA Top Level Goal	General Area of Contribution	In-depth Area of Contribution
<b>3.1 MFE Goal 1:</b> Advance understanding of plasma, the fourth state of matter, through well-diagnosed experiments, theory and simulation	<b>3.1.1 Turbulence and Transport:</b> Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems	<b>3.1.1.2 Understanding Transport Barriers</b> – explore roles of magnetic and velocity shear
	<b>3.1.2 Macroscopic Stability:</b> Develop detailed predictive capability for macroscopic stability including resistive and kinetic effects	<b>3.1.2.1 Understanding Observed Macroscopic Stability Limits</b> – use current profile control to understand limits to operation near $\beta_n$ limit
	<b>3.1.3 Wave-Particle Interaction:</b> Develop fundamental understanding of plasma heating, flow, and current drive, as well as energetic particle instabilities,..., especially for reactor-relevant regimes.	<b>3.1.3.1 Plasma heating and Current Drive</b> – Check theory of current drive by lower hybrid waves, e.g., $f(\mathbf{v}, \mathbf{r})$ . Investigate off-axis current drive and bootstrap current, and sustainment for $\sim L/R$ time scale.



# Lower Hybrid Experiments on C-MOD Will Make Substantial Contribution to IPPA Goals



IPPA Top Level Goal	General Area of Contribution	In-depth Area of Contribution
<b>3.3 MFE Goal 3:</b> Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.	<b>3.3.1 Profile Control:</b> Assess profile control methods for efficient current sustainment and confinement enhancements, consistent with efficient divertor operation, for pulse length $\gg \tau_E$ .	<b>3.3.1.1 Plasma Current Profile:</b> Develop consistent models of self (bootstrap) and LH driven current. Seek to demonstrate states of higher plasma density.
		<b>3.3.1.2 Plasma Pressure Control:</b> Explore use of variable frequency ICRF heating in conjunction with current profile control to improve plasma confinement and stability
	<b>3.3.2 High <math>\beta</math> Stability and Disruption Mitigation:</b> Develop and assess high- $\beta$ instability feedback control methods and disruption control & amelioration in the AT, for $T_{\text{pulse}} \gg \tau_E$ .	<b>3.3.2.3 Active Profile Control to Avoid External Boundaries:</b> Use active control of current and pressure profiles to maintain profiles stable to known operational boundaries.